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# SOME ASPECTS OF THE STRUCTURE AND DYNAMICS OF THE TERRESTRIAL MAGNETOSPHERE

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# I. THE INTERPLANETARY MEDIUM

The suggestion that the sun continuously emits corpuscular radiation (the "solar wind") was made by Biermann[1] as an explanation of the fact that gaseous comet tails tend to trail directly away from the sun. It had been known for many years that magnetic storms must be the result of isolated bursts of corpuscular radiation, and the fact that some aurora and geomagnetic disturbance always occurs at high latitudes may be considered as additional evidence that the radiation is continuous. Biermann's suggestion was taken up by Parker[2] who examined the dynamics of the solar wind and showed that it may be considered as a hydrodynamic expansion of the solar corona and a direct consequence of supplying heat to maintain the corona at its observed temperature. There is certainly no possibility that sun has a static corona as suggested by Chapman[3].

Early estimates of the density and speed of the solar wind were understandably rather variable. However we now have direct evidence from space probes[4] which confirms the existence of the solar wind and shows its flux to be of the order of $10^{8}$-$10^{9}$ cm$^{-2}$ sec$^{-1}$ during relatively quiet periods, rising to $10^{10}$ cm$^{-2}$ sec$^{-1}$ during magnetic storms. The solar winds speeds range from 300-800 km sec$^{-1}$ and the densities are 5-10 protons cm$^{-3}$; the motion is apparently supersonic with a Mach number of $\sim 5$. There is no direct evidence that the solar wind moves other than radially from the sun. The solar magnetic field is relatively weak, being $\sim 5\gamma$ at 1 a.u. during quiet periods, and $\sim 50\gamma$ during magnetic storms[5]. As a consequence of solar rotation and the radial motion of the solar wind the solar magnetic field lines take the form of a spiral, and may be considered as rotating rigidly with the sun. The latter effect causes an anisotropy in the cosmic radiation which provides a means of determining the solar wind speed without having recourse to space probes[6].

Sudden heating due to a flare on the sun must enhance the expansion of the corona, and result in the formation of an outwards -- moving shock wave in the interplanetary medium (2,10). The shock wave, together with the associated increase in solar wind speed and density, produces a magnetic storm as it interacts with the geomagnetic field. Localized enhancements of the solar wind may occur due to "hot spots" in the corona; these may persist for several solar rotations and are believed to cause magnetic storms which repeat over a 27 day period (44). The leading edge of such a region of enhanced solar wind must form a shock wave on interacting with the normal solar wind, and it is easy to see that the shape of the shock wave must be a spiral making a slightly smaller angle with the radial direction than the solar magnetic field lines. This shock wave ensures that the resulting magnetic storm has a sudden commencement, as do the storms associated with transient heating of the corona. Its curved shape causes the storms to occur some days after central meridian passage of the "hot spot" around the sun.

## II. THE MAGNETOSPHERE

### A. Cavity Formation

The magnetohydrodynamic concept according to which magnetic field lines are "frozen" into a perfectly conducting fluid, makes it apparent that the geomagnetic field must produce a cavity in the solar wind--the whole of this cavity down to an altitude of about 100 km., forms the earth's magnetosphere. Clearly it is an important prerequisite to an understanding of magnetospheric phenomena that we should know as much as possible about the shape and structure of the cavity. This is not easy however, as cavitation problems in fluid dynamics are notoriously difficult, but we can make some theoretical predictions, and direct observations from space probes are now beginning to add considerably to our knowledge.

A few solutions to cavitation problems in magnetohydrodynamics are known; these concern incompressible flow of perfectly conducting inviscid fluid in two dimensions. The cavities produced as a result of uniform flow past a two-dimensional magnetic dipole[7] and a line current[8] are shown in figure (1). At the boundary of such cavities the normal pressure (fluid plus magnetic) must be continuous. It should be noted that in each case the pattern is symmetrical and the direction of flow therefore reversible--this is a consequence of the neglect of dissipative effects. However, in the case of the magnetosphere even if dissipative effects at the boundary are ignored, we still have to contend with the three-dimensional nature of the problem and the fact that the solar wind is highly supersonic.

B. Shock Waves

It is necessary to consider the solar plasma as a continuum rather than a 'free molecular' or 'Newtonian' flow in its interaction with the magnetosphere since collective motions such as plasma oscillations and magnetohydrodynamic waves can occur with wavelengths much smaller than the typical length scale involved (that is, about $10^5$ km). Thus since the solar wind is supersonic, some form of shock wave must be produced on the upstream side of the magnetosphere[9]. This reduces the bulk velocity of the plasma to a low subsonic value near the forward stagnation point and permits the plasma to flow around the magnetosphere. The motion of the plasma eventually becomes supersonic once again on the flanks of the magnetosphere, although the free stream conditions may not be regained. It should be noted that the shock wave is an irreversible phenomenon and hence the magnetosphere can be expected to be nonsymmetrical even if all other dissipative processes are neglected.

This shock wave and also the shock wave which is believed to cause the sudden commencement of a magnetic storm[10] must be of the type known as "collision free". It is unfortunate this term has been allowed to come into common usage as it is rather misleading. In an ordinary non-ionized gas the collision frequency of molecules and the highest possible frequency of a sound wave are essentially the same -- thus the steepening of a compressive pulse is halted when its width becomes comparable to the mean free path. In a plasma, however, one tends to equate the mean free path to the distance a particle must travel in quiescent plasma before its momentum is significantly altered, whereas sound waves do not become heavily attenuated until the product of their frequency and the electron - ion collision frequency becomes comparable to the product of the electron and ion gyro-frequencies. Thus a compressive pulse in a plasma can steepen until its width is much less than the mean free path, although thermal equilibrium may not be restored until the plasma has moved through the latter distance. The processes underlying shock waves in a plasma are by no means understood, however it is usually considered that non-linear interactions of waves produced by instabilities cause the required randomization of particle motions[11]. The shock structure and the region downstream should therefore appear to be highly turbulent and bursts of supra-thermal particles may occur.

## C. Theoretical Discussion of the Structure of the Magnetosphere

It is generally agreed that the magnetosphere must have a more or less tear drop shape as indicated in figure (2), -- the first to suggest this being Johnson[12] and Piddington[13]. However, it is not always realized that such a magnetosphere is likely to have essentially the same topological features as the early model of Chapman and Ferraro[14] which made use of an image dipole to distort the geomagnetic field into an infinite half-space. Details of the Chapman-Ferraro model are shown in figure (3). The main features to notice are that all field lines on the surface of the region of magnetic field run between two neutral points ($N_n$, $N_s$) which are in turn connected by a single field line to points ($M_n$, $M_s$) at high latitudes on the central (noon) meridian of the earth. Field lines which intercept the earth at higher latitudes than $M_n$, and $M_s$ are shown shaded -- these constitute the geomagnetic "tail." The low latitude field lines (unshaded region) form a donut around the earth and are completely enclosed by the field lines forming the tail. Obviously a uniform solar wind must cause the magnetosphere to take up a shape more or less as sketched in the figure (2). However, this distortion is not likely to change the topology of the magnetic field from that of the Chapman-Ferraro model. In particular, all the features described above should be retained and thus we have labeled and shaded the various diagrams in a similar manner to make this apparent. It is interesting to note that Hones[15] has recently produced a more sophisticated version of the Chapman-Ferraro model using parallel unequal dipoles so that the field of the stronger dipole completely encloses that of the weaker, which is taken to be the geomagnetic field; not surprisingly, this model also retains all the topological features of the simple image dipole model.

Exact details of the structure and dimensions of the magnetosphere cannot be given as these must take proper account of the flow of solar plasma around the magnetosphere and this cannot be done with present methods. However, this is not a great disadvantage as one can easily made rough estimates of several key dimensions of the magnetosphere. It is known from hypersonic flow theory[16] that the pressure at the stagnation point O is approximately

$$P = KnmV_s^2 , \tag{1}$$

where n is the number density of protons in the solar wind, m is the mass of a proton, $V_s$ the speed of the solar wind, and K a numerical factor which is almost unity. This must equal the magnetic pressure at the boundary of the magnetosphere (if we neglect the interplanetary magnetic field and the pressure of magnetospheric gas), which according to the image dipole model is $H_e^2/2\pi R_o^6$, where $H_e$ is the magnetic field strength at the equator of the earth and $R_o$ is the geocentric distance to the stagnation point. Thus if $R_e$ is the radius of the earth,

$$R_o/R_e \simeq H_e^{1/3} / (2\pi\ KnmV_s^2)^{1/6} \quad . \tag{2}$$

Taking $H_e$ = 0.32 gauss, $V_s$ = 300 km/sec and n=10 $cm^{-3}$, it is found that $R_o \simeq 10R_e$. The value of $R_o$ is increased slightly if the surface of the magnetosphere is taken to be hemispherical rather than flat.

For reasons which are not entirely understood, a fair approximation to the solar wind pressure at not too great a distance from the stagnation point is given by

$$p = KnmV_s^2 \quad \mathrm{Cos}^2\ \theta, \tag{3}$$

where cos $\theta$ is the angle between the solar wind direction and the normal to the surface of the magnetosphere. This pressure variation is the same as for flow past a circular cavity shown in figure (1) and we are therefore led to expect that the surface field line $N_n ON_s$ is approximately a circular arc, although it should be remembered that the accuracy of (3) falls away rapidly as cos $\theta$ diminishes. The geocentric distance ($R_1$) to the boundary in the equatorial plane perpendicular to the sun-earth direction must be somewhat greater than $R_o$ since the pressure is decreased from the stagnation point value because the solar plasma accelerates as it passes around the magnetosphere and is probably supersonic at this point; Harrison[17] suggests

$$R_1 \simeq (3\pi/4)^{1/3} R_o . \qquad (4)$$

A rough estimate of the latitude ($\lambda_M$) of the points $M_n$ and $M_s$ can be obtained from the relationship

$$K' R_o \cos^2 \lambda_M = R_e , \qquad (5)$$

where K' lies between 1 and 2. Taking K' = 2 then $\lambda_M = 77°$ when $R_o = 10R_e$, and a variation between 70° and 80° can be expected according to the solar wind pressure. Since all field lines intersecting the earth at latitudes greater than $\lambda_M$ must form the geomagnetic tail, then if $\lambda_M$ is as small as 70° the tail must extend to 60 $R_e$ in the antisolar direction, assuming the average width of the magnetosphere to be 20 $R_e$ and the average field strength in the tail to be 30γ. This assumes that the component of the magnetic field perpendicular to the equatorial plane is 30γ, however it is possible that the tail could be much longer if the field lines lie mostly parallel to the equatorial plane; if so, the tail could be as much as 20 $R_e$ in radius if the field is 20γ and $\gamma_M$ has the more modest value of 75°.

A number of workers have calculated the approximate shape of the magnetosphere assuming a Newtonian solar wind with specular reflection of particles incident on the surface (18,19). In this case (3) holds everywhere and K is taken to be 2. The shape of the magnetosphere appears to be rather insensitive to the physical nature of the exterior wind, and the results of such calculations (if done correctly (20)) are not substantially different from what has been described above, apart from the discrepancy in K. In particular one does not expect any significant deviation from the topological features exhibited by the Chapman-Ferraro model.

The question of whether or not the magnetosphere is stable is of some significance. Analyses based on the assumption of specular reflection of solar wind particles suggest that the surface is unstable in the Helmholtz manner (21,22). However the equivalent continuum solution (23) suggests that the surface could be stable when the relative velocity is sufficiently low. Dessler (26) has argued that the surface is stable on the basis of the steadiness of low-latitude magnetograms during magnetically quiet periods when the solar wind is presumed to be relatively steady. However there is no good reason for believing that the affects of any instability would be noticable at low latitudes, while it is known that high-latitude magnetograms show continuous disturbance at all times. Since the relative velocity of the solar wind and the surface of the magnetosphere is greatest on the afternoon side of the magnetosphere (see figure (9)), one would expect instability to occur in this region if anywhere. The instability would be observable only as a waviness of the surface of the magnetosphere since any small scale "spray" would probably be indistinguishable from the interplanetary medium. Rayleigh-Taylor instability due to the acceleration of the surface of the magnetosphere during a magnetic storm sudden commencement may also occur (9), however it would be short-lived and very difficult to observe directly.

D. Observations of the Shape of the Magnetosphere.

Space probe observations are now beginning to confirm the general picture of the magnetosphere which has been outlined here. There is unfortunately very little information about the state of the geomagnetic tail, however a good deal is known about the magnetic field structure on the sunwards side of the magnetosphere.

The earliest suggestions of the occurrence of a region of turbulent plasma lying between the surface of the magnetosphere and the standing shock wave produced by the solar wind came from Pioneer I[25], and Pioneer IV[26]. The Geiger counter record from Pioneer IV shows what is apparently trapped radiation out to about 60,000 km. in the sunwards direction, a region of fluctuating counting rate between 60,000 km. and 90,000 km., and a steady count beyond 90,000 km. (figure (4)). We interpret the counts in the intermediate region as being due to bremsstrahlung from electrons with energies of the order of tens of kev. produced by random electric fields in the turbulent plasma behind the standing shock wave. The steady count beyond 90,000 km. is apparently the cosmic ray background. The magnetometer on Pioneer I showed similar effects, although the record is not continuous - the portion of the record taken at 12.6 $R_e$ shows the strong fluctuations characteristic of the turbulence behind the shock wave while the record at 14.8 $R_e$ shows a much smaller and quieter field which one would associate with undisturbed solar wind (figure (5)).

More recently, observations from Explorer XII have shown the surface of the magnetosphere to be quite well-defined, in terms of both the magnetic field[27] and trapped electrons[28]. (figure (6)). A remarkable feature of the magnetic measurements is that the magnetic field tends to reverse its direction at the magnetospheric boundary - no satisfactory explanation of this effect has yet been proposed. These results have been extended by Explorer XIV[29], the orbit of which makes much greater angles with the sun - earth line than Explorer XII. A summary of the electron flux measurements (for energies $\gtrsim$ 40 kev.) is given in figure (7). Note that the magnetosphere is indeed wider perpendicular to the sun-earth line in the equatorial plane than it is in the sun-earth direction. Also the electron flux appears to be low in the interior of the geomagnetic tail, and increases towards the surface. In the low-latitude region, the lines of constant flux are somewhat asymmetric with respect to day and night, and a rapid decrease of flux occurs on the midnight meridian at about 7 $R_e$, which is rather closer than the boundary of the magnetosphere on the noon meridian ($\sim$ 10 $R_e$). This effect, which was observed earlier at low altitudes by Injun I[30], may be due partly to the asymmetry of the magnetic field, and partly to the effect of electric fields which drive the particles towards lower latitudes, as will be explained in a later section.

The boundary of the magnetosphere was first observed by Explorer X, which passed through it at a distance of about 40 $R_e$ on the downstream flank of the magnetosphere well below the equatorial plane[31,32]. Within the boundary the magnetic field was observed to be relatively steady, while outside it was weaker and highly disturbed, and a supersonic flow of plasma (presumably the solar wind) always appeared. The boundary moved across the trajectory of the satellite several times, possibly as a result of changes in the solar wind, or alternatively as a result of a large scale waviness of the boundary. A striking feature of the Explorer X observations is that the geomagnetic field at great distances from the earth is almost radial, and that there was no sign of the magnetosphere closing on itself. The geomagnetic tail must therefore be very extensive, and there is a likelihood of interesting effects taking place near the equatorial plane in the tail region, which may almost be a magnetically null surface.

The results obtained from Russian space probes are on the whole disappointing. Gringauz and his colleagues[33] have reported the existence of a 'third radiation belt' which may be connected with the turbulent region between the magnetospheric boundary and the standing shock wave, however the concurrent magnetic measurements did not make this clear. There is one particularly interesting feature of the current trap measurements[34], namely that an 'edge' occurs in the low energy material (the whistler medium) at a distance of about 4 $R_e$ (see figure (8)). The existence of a 'knee' in the magnetospheric ionization density profile has also been deduced from whistler measurements by Carpenter[35], who suggests that it exists at all times, and tends to move inwards towards the earth with increasing magnetic activity.

The question of the stability of the surface of the magnetosphere is not entirely resolved, although as Dessler[36] has pointed out, the well-defined 'edge' observed by Explorers XII and XIV suggests that small scale instabilities do not occur on the sunwards side of the magnetosphere. However the possible waviness of the boundary on two afternoon flank of the magnetosphere, observed by Explorer X may be due to a form of Helmholtz instability, and one would expect this to be even more pronounced further downstream.

# III. MOTIONS IN THE MAGNETOSPHERE

## A. Theoretical Aspects

It is a most significant feature of the magnetosphere that the energy density of the gas it contains is usually everywhere much less than the energy density of the magnetic field, thus the magnetic field dominates the mechanics of the interior of the magnetosphere. That is, the magnetosphere has a shape determined by the solar wind and the attitude of the earth relative to the sun, and provides a sort of magnetic framework which is largely unaffected by internal processes. In fact this is not always exactly true as the gas pressure is believed to become significant occasionally due to the temporary trapping of large numbers of energetic particles during the main phase of geomagnetic storms, producing the so-called "ring current" effect; even in this case, however, the gas pressure probably never exceeds the magnetic pressure.

One might be tempted to believe that the only motions open to low energy charged particles in the magnetosphere are those which take place along field lines since the magnetic field is relatively strong and apparently firmly fixed in the solid earth. However, as pointed out by Gold[37] the notion of material being "frozen" to magnetic lines of force is rather misleading in this instance since the highly conducting earth is separated from the magnetospheric plasma above 100 km altitude by a shell of non-conducting atmosphere in which there is no "freezing" and lines of force cannot be identified. Consequently, motion of magnetospheric plasma is permitted provided the plasma and magnetic field are considered as frozen only down to E region levels, and the magnetic field remains continuous with the field in the non-conducting atmosphere. The fact that the magnetic field is strong does not prevent motion of the plasma but does impose a restraint, in that only those motions for which the energy change of the magnetic field is compatible with what is available in the form of gas energy are permitted. These are the "interchange" motions in which tubes of force with enclosed plasma may be considered as permuting in such a way that the magnetic field appears unaltered. Since the magnetic field is not uniform such motions necessarily involve changes of volume of the tubes, with corresponding energy changes in the plasma they contain -- this appears to be an important energization process for the magnetospheric material.

These concepts can be readily understood from the electrodynamic point of view[38,39]. The appropriate equations of mean motion for low energy ions are

$$MD\underline{V}_{\perp}/Dt = e_i(\underline{E}_{\perp} + \underline{V}_{\perp} \times \underline{B}) - MK_n(\underline{V}_{\perp} - \underline{V}_{\perp n}) \qquad (5)$$

$$MDV_{\parallel}/Dt = e_i E_{\parallel} - MK_n(V_{\parallel} - V_{\parallel n}), \qquad (6)$$

where M is the mass of an individual ion, $e_i$ is its charge, $K_n$ the 'frictional' frequency (related to the collison frequency) of the ions with neutral particles, $\underline{V}_n$ the mean velocity of neutral particles, $\underline{V}$ the mean velocity of the ions, $\underline{E}$ the electric field and $\underline{B}$ the magnetic induction. The subscripts $\perp$ and $\parallel$

refer to the directions perpendicular and parallel to the magnetic field respectively. We have ignored collisions between charged particles, partial pressure gradients, viscous effects, and gravity, although each of these may be important in restricted regions. A similar set of equations hold for electrons. On considering the order of magnitude of the various terms it can be readily seen that provided the frequencies of the mean motion are small compared with the gyro-frequency $e_i B/M$ the "inertia" term on the left of equation (5) can be neglected. Throughout most of the magnetosphere (namely above about 150 km. altitude) the frictional frequency for ions is also small compared with the gyro-frequency, and this is true for electrons down to 80 km. altitude; thus for all particles above 150 km. the equation of motion reduces to

$$\underline{E}_{\perp} + \underline{V}_{\perp} \times \underline{B} = 0. \tag{7}$$

In the "dynamo" region between altitudes of 90-140 km. the frictional frequency for ions is large compared with the gyro-frequency and equation (5) may be written approximately as

$$e_i \underline{E}_{\perp} - MK_n (\underline{V}_{\perp} - \underline{V}_{\perp n}) = 0, \tag{8}$$

while the electrons obey (7). Along the field lines, particles accelerate in a quasi-steady electric field until collisions become significant and the inertia term on the left of (6) may be neglected; thus

$$e_i E_{\parallel} - MK_n (V_{\parallel} - V_{\parallel n}) = 0. \tag{9}$$

Since the frictional frequency is small throughout most of the magnetosphere, it is reasonable to reduce (9) further to $E_{\parallel} \simeq 0$, although small departures from this exact condition may have interesting effects.

As a consequence of (7) all constituents above about 150 km. altitude move approximately with mean velocity

$$\underline{V}_{\perp} = \underline{E}_{\perp} \times \underline{B} / B^2. \tag{10}$$

We describe this as the "motion" of lines of force with the plasma which identifies the lines being frozen to them, since the application of

$$\partial \underline{B} / \partial t = \text{curl } \underline{E} \tag{11}$$

to (7) leads to a relation which is analogous to Kelvin's vorticity theorem in ordinary hydrodynamics. In quasi-steady conditions $\underline{E}$ is derivable from a potential such that

$$\text{grad}_{\perp} \phi = \underline{V}_{\perp} \times \underline{B} ; \tag{12}$$

hence the lines of force and the streamlines of the motion must be equipotentials of the electric field.

Below 150 km. altitude, the electrons can still be considered as frozen to the lines of force down to 90 km., and they therefore move perpendicular to $\underline{E}_{\perp}$, according to (10). The heavy ions however can drift only slowly relative to the neutral gas in the direction of the electric field, as indicated by (8). Thus there is a Hall current perpendicular to the electric field carried mainly by the electrons, and a much smaller direct (Pedersen) current parallel to the electric field carried mainly by the ions. We can therefore interpret ionospheric current systems as indications of the presence of large scale electric fields and these in turn imply motions elsewhere in the magnetosphere as given by (10). If there were no motion of the neutral atmosphere ($\underline{V}_n = 0$) it would be possible to interpret the current systems directly in terms of motions of the "feet" of lines of force in the magnetosphere since the predominance of the Hall current would require only the reversal of the sense of the current system to give the flow lines. However, when $\underline{V}_n = 0$, and particularly when $\underline{V}_n$ and $\underline{V}$ are comparable, this procedure may be very difficult as the motion of the neutral atmosphere at ionospheric levels is not very well known.

In this discussion we have neglected the effects of the movement of plasma on the neutral atmosphere. Although the density of neutral gas in the ionosphere is much larger than that of the ionized gas, given sufficient time the latter can force the former into motion. In fact the time required is not long in comparison with most periods of interest here, being about 20 minutes in F region of the ionosphere and several hours in the E region.

B. <u>Energization of Charged Particles due to Motions in the Magnetosphere</u>

We have suggested above that changes in volume associated with magnetospheric motions in which tubes of magnetic flux are permuted, cause changes in the energy of the particles concerned. In fact the energy changes take place in such a manner that the magnetic moment and 'longitudinal' adiabatic invariant of the individual particles are conserved. It is the nonuniformity of the magnetic field which leads us to speak of "changes in volume" causing energy changes. Not surprisingly, if we consider the motion of individual particles it is this nonuniformity which causes the energy changes, since the motion of the particles is given by

$$\underline{v} = \underline{E} \times \underline{B}/B^2 + \underline{v}_d \tag{13}$$

if we ignore electric fields parallel to the magnetic field lines. $\underline{v}_d$ is the drift due to non-uniformity of the magnetic field-- this is energy and charge dependent, and it is more or less in the longitudinal direction in the case of the geomagnetic field. All particles take part in the $\underline{E} \times \underline{B}/B^2$ motion and this in itself does not produce any change in energy since the motion is along equipotentials of the electric field. However the energy dependent drift $\underline{v}_d$ does in general cause the particles to move across these equipotentials and changes in energy occur accordingly.

Low energy particles follow the $\underline{E} \times \underline{B}/B^2$ motion quite closely, and the longitudinal drift can be considered as a perturbation of this motion. For high energy particles the $\underline{v}_d$ drift is more significant than the electric field drift and hence their motion may be considered as more or less longitudinal with perturbations due to the electric field. The total electric potential variation associated with the electric field gives us a measure of the maximum amount of energy which can be given to a particle as a result of the magnetospheric motion--this is usually of the order of tens of kilovolts, and thus the maximum energy change for any particle due to this process is of the order of tens of kev. Particles with energy greater than about 100 kev are therefore only moderately perturbed by the magnetospheric motion, but particles of energies of about 1 kev will tend to follow magnetospheric motion quite closely. Further discussion of these processes can be found in papers by Hines[40], Dungey[41], and Sonnerup and Laird[42].

The type of energy change we have described takes place reversibly, with the energy of the particle increasing as it is carried to lower geomagnetic latitudes. However it seems fairly certain that in addition, irreversible energy changes take place due to fluctuations in the electromagnetic environment of the particle, and these lead on the average to a general increase of energy with time. Thus in considering the effects of magnetospheric motions it should be realized that although the motion might ideally cause 1 kev particles to be carried into the interior of the magnetosphere and be energized to perhaps 20 kev in doing so, irreversible processes can be expected to increase the energy to a much greater level if sufficient time is available and the motion does not carry the particle out too soon. Consequently the net effect of such motions is irreversible and leads to the accumulation of energetic particles in the interior of the magnetosphere if they can escape precipitation into the atmosphere.

C. Rotational Motion of the Magnetosphere

Due to viscous effects, the rotation of the earth is impressed upon the upper atmosphere. The electrons and ions of the ionosphere also take part in this motion and the electric field generated is transmitted throughout the magnetosphere since, as described above, the magnetic field lines must be equipotentials in quasi-steady conditions. The equipotentials in the equatorial plane of the magnetosphere corresponding to rotation are shown in figure (9). It should be noted that the low latitude donut co-rotates with the earth more or less rigidly, while the high latitude field lines which form the geomagnetic tail "twiddle" around so that the sense of rotation in the equatorial plane is reversed.

The total electric potential variation between the equator and the poles is 88 kilovolts of which only about 10-15 kilovolts are associated with the geomagnetic tail (depending on the value of $\lambda_M$). The gradient of this electric potential, however, becomes very large in the tail as the outer surface of the magnetosphere is approached. This can easily be seen from the following argument[43]. The time taken to complete a circuit of any streamline or equipotential is 24 hours. Since the electric field and the magnetic induction are continuous in the interior of the magnetosphere, field lines with feet at latitude $\lambda_M$ (which therefore lie exactly on the surface dividing the low latitude donut from the geomagnetic tail) take 24 hours to cover the portion of the streamline which lies inside the magnetosphere. The remaining portion which forms the surface of the magnetosphere should ideally be completed at infinite speed, corresponding to a very large electric field or potential gradient, although dissipative effects must prevent the singularity from actually occuring.

D. Motions Corresponding to the Current Systems $S_q$ and L.

It is believed that the ionospheric electric current systems $S_q$ and L are induced by motions of the neutral atmosphere due to solar and lunar tidal effects respectively; the lunar tide is probably a gravitational phenomenon but the solar tide may be a consequence of atmospheric heating[39]. The $S_q$ current system is shown in figure (10) and the lunar-induced system is rather similar but much weaker[44]. Diagrams of this type are deduced from the magnetic variations assuming that the currents are closed within the ionosphere and that currents which flow along lines of force between conjugate points can be neglected. These assumptions are inaccurate[45] but the general picture of the current system so found is probably reasonably correct.

The $S_q$ system produces the most significant motions that occur at low latitudes and as it is possible that the motions of the neutral atmosphere are relatively weak at these latitudes, the magnetospheric motion may be derivable with reasonable accuracy from the current system. Thus we see that there is motion in the magnetosphere from east to west at the equator during the day with a movement of the feet of lines of force towards higher latitudes in the morning and lower latitudes in the evening.

When combined with rotation, (see figure (10)), it can be seen that a closed cell is formed at the equator on the sunward side of the magnetosphere. It seems likely that the motion away from the equator before noon is partly the cause of the curious diurnal variations of the equatorial F region ionization[46]. The lunar current system L is much weaker than $S_q$ and the corresponding magnetospheric motions are accordingly little more than a perturbation of the pattern sketched in the slide; however the perturbation does appear to be noticeable at times in that L influences the intensity of sporadic E ionization associated with the equatorial electrojet[47].

E. Magnetospheric Motions Associated with Polar Current Systems

The most intense magnetospheric currents at high latitudes are those forming the $D_s$ system which appears during magnetic storms[44]. A somewhat idealized sketch of the pattern of currents is given in figure (11), where it will be noticed that on reversing the arrows the sense of motion on the night side is in accord with what is observed for ionization irregularities associated with the aurora[48]. The corresponding motion in the equatorial plane of the magnetosphere is also sketched in figure (11), where it can be seen that the plasma moves past the earth from roughly the anti-solar direction toward the sun. The total variation in the electric potential appears to be of the order of 20 kilovolts[49].

There is some controversy concerning the origin of the $D_s$ current system. We will shortly consider the hypothesis that the motions and currents are driven by the solar wind. However, some authors suggest a purely tidal mechanism[50] and others suggest that the radiation belts are involved[51,57]. There seems nevertheless no doubt that this current system with its associated magnetospheric motions contains the key to an understanding of the phenomenon of the aurora and probably to the origin of much of the trapped radiation.

Whatever the mechanism of the $D_s$ current system, it would be surprising if there were not some vestige of it even during magnetically quiet periods. This has recently been found by Nagata and Kokubun[52] who give it the symbol $S_q^p$ and show that it has essentially the same pattern as the $D_s$ system (figure (12).

F. <u>Conjugate Point Variations</u>

Small differences of electric potential between conjugate points in the northern and southern hemispheres tend to be annulled by currents flowing with little resistance along the lines of force. If, however, the potential difference is maintained by some process such as an atmospheric tide, the current is continuous and it imparts a twist to the field lines which is uniform along their length. Even if the angle of the twist is quite small the great length of geomagnetic field lines, at high latitudes especially, can result in a considerable displacement of the ends of the field lines from their normal position. Thus diurnal and seasonal variations can be expected in the apparent conjugate points obtained by methods such as riometer techniques, since much of the absorption observed depends on the penetration of energetic electrons into the atmosphere and these in turn move along lines of force in the magnetosphere.

Information causing changes in the electrical potential on a magnetic line is propagated in the form of hydromagnetic waves. A transient change in the potential in the ionosphere at one end of the field line can therefore lead to the formation of a wave which may travel back and forth along the field line a number of times if dissipation at the ends is not too great. Some low frequency emissions can be expected to be produced in this way from ionospheric variations.

# IV. DISTURBANCE PHENOMENA IN THE OUTER MAGNETOSPHERE.

## A. The Theory of Axford and Hines.

Axford and Hines[38] have suggested that the basic processes underlying high latitude disturbance phenomena (including the aurora) is the motion in the magnetosphere associated with the $D_s$ current system. It is proposed that this motion, which is sketched for the equatorial plane of the magnetosphere in figure (13), is due to a viscous-like interaction between the solar wind and the surface of the magnetosphere. This interaction produces an internal circulation in the interior of the magnetosphere rather similar to that occurring in a falling rain drop. Note that the dragging of lines of force around the surface of the magnetosphere cannot be very noticeable at ionospheric levels due to the fact that, ideally anyway, the surface field lines are connected to only one point in each hemisphere; hence only the internal part of the circulation is evident in the form of the $D_s$ current system and, at quiet times, the $S_q^p$ current sytem.

There are obvious merits to the suggestion. In the first place, the circulation provides a simple and effective accelerating mechanism which can energize captive solar wind particles from about 1 kev up to 10 kev (corresponding to conservation of magnetic moment between fields of $50\gamma$ at the magnetospheric surface and $500\gamma$ at a distance of $4R_e$). Secondly, the polar current systems and the pattern of alignment of auroral arcs at high latitudes (figure (14)) are reproduced by the circulation at ionospheric levels, giving us some understanding of the nature of the current systems and their relationship to the motion of auroral irregularities. Thirdly, by combining the circulation with the motion associated with the rotation of the earth, it is possible to predict qualitatively much of the morphology of many high latitude disturbance phenomena. Finally, the circulation in combination with irreversable accelerating processes provides an input mechanism for the outer zone of geomagnetically trapped radiation.

In the view of Axford and Hines a magnetic storm can be considered as consisting of the sudden commencement due to the passage of a shock wave heralding enhanced solar wind density and velocity, an initial phase due to the increased solar wind pressure and a main phase caused by the trapping and energization to 20 kev or so of solar wind particles thus producing a "ring current"[54]. The decay of the main phase takes place as the solar wind returns to normal and energetic protons are lost from the ring current due to charge exchange with neutral hydrogen atoms[54], or perhaps to de-energization associated with movement to outlying parts of the magnetosphere.

We will not discuss all the implications of the theory here, as these are to a large extent covered elsewhere (38, 39, 40, 63, 69, 55). Instead, we will confine our attention to the viscous interaction hypothesis itself and to the morphology of disturbance phenomena. However, it is pointed out in passing that a circulation of the type we are considering would contribute to the effect observed by O'Brien[30], and others[24], which implies that the high latitude boundary of the trapped electrons (energies $\geqslant 40$ kev) occurs further from the pole on the midnight magnetic meridian than it does on the noon magnetic meridian. The circulation is such that it carries all trapped particles to lower latitudes on the night side of the earth and to higher latitudes on the day side -- this would therefore complement the mechanism of Reid and Rees[56] which relies on the effect on the longitudinal adiabatic invariant of stronger fields at a given latitude on the day side of the magnetosphere than on the night side.

B. The Viscous Interaction Hypothesis

Fejer[51,57] and others[58,59,60] have proposed alternative mechanisms to viscous interaction between the solar wind and the magnetosphere as an explanation of the $D_s$ current system and the associated ionospheric motions. Whether or not such mechanisms contribute to the circulation, viscous interaction must in any case occur to some extent[61] and the following argument suggests that it is strong enough to produce effects which are consistent with observations.

There are two principal quantities associated with the various phenomena under discussion. These are the total electrical potential variation ($\phi$) corresponding to the magnetospheric motions, and the rate of dissipation of energy ($\Phi$) resulting from such motions[69]. The speed of auroral motions, the strength of the $D_s$ current system, the position of the auroral zone, and the energy of primary auroal particles, all suggest that $\phi$ is of the order of 20 kilovolts during a typical magnetic storm. In the same conditions $\Phi$ is at very most $10^{19}$ ergs/sec according to estimates of energy dissipation due to auroral processes, joule heating of the atmosphere by the ionospheric currents, and stressing of the geomagnetic field by the accumulation of trapped particles which are later lost. As might be expected, $\Phi$ is several orders of magnitude less than the solar wind energy incident per second on the magnetosphere.

A series of simple arguments based on viscous boundary layer theory adapted from ordinary hydrodynamics and using very reasonable values for various relevant parameters, shows that the thickness of the boundary layer associated with the observed value of $\phi$ is typically 500 km, the kinematic viscosity associated with the interaction is $\sim 10^{13}$ $cm^2/sec$, the drag per unit surface area of the magnetosphere about $2 \times 10^{-10}$ $dynes/cm^2$ and the energy dissipation rate about $10^{19}$ ergs/sec.

The fact that the viscous interaction hypothesis shows that the values of $\phi$ and $\Phi$, deduced independently from observed quantities are compatible, is in itself remarkable enough. In addition it can be shown that the actual drag to be expected at the surface of the magnetosphere, based on observed characteristics of the solar wind, is consistent with the value estimated from the observed value of $\phi$. This drag is believed to be due to the highly turbulent state of the solar wind after it has passed through the standing shock on the sunward side of the magnetosphere. The energy density associated with longitudinal (sound) waves in the turbulence is $\sim 10^{-9}$ $ergs/cm^3$ [62]. These sound waves can penetrate the surface of the magnetosphere and if there is a relative motion the residual radiation stress parallel to the surface causes a drag which a rough calculation suggests is of the order of $10^{-10}$ dynes/cm$^2$ -- that is, within a factor 2 of the value required if $\phi$=20 kilovolts.

In figure (13) we have shown the circulation within the magnetosphere to be symmetrical about the sun-earth direction. In fact this is not completely correct since the surface of the magnetosphere tends to move quite rapidly due to the rotational effect described earlier. Any viscous-like interaction between the solar wind and the surface of the magnetosphere depends on the relative velocity, and this is clearly affected by the rotationally-induced motion in the magnetosphere as well as by the solar wind. The point of zero relative velocity on the surface of the magnetosphere is consequently well to the west of the subsolar point, and the viscously-induced circulation is therefore likely to be roughly symmetrical about this direction, although it may be stronger on the afternoon side than on the morning side of the magnetosphere[43]. This may be the explanation of the tendency of the polar current systems and the sudden commencement currents at high latitudes to be symmetrical about a direction which lies 40° - 50° to the west of the sun[52,63,64].

## C. The Morphology of High Latitude Disturbance Phenomena.

Relative to the earth, the magnetospheric circulation at ionospheric levels during periods of high magnetic activity, has essentially the pattern of the $D_s$ current system, with of course the sense reversed from that of the current. As can be seen from figures (11) and (14), this reproduces the observed motion of irregularities in the aurora (to the west before geomagnetic midnight and to the east after geomagnetic midnight). Furthermore if there is any correspondence between the direction of the motion and the alignment of auroral arcs, as there is in the auroral zone, the pattern is consistent with the tendency of arcs in the polar caps to be aligned roughly in the sun - earth direction[53].

The net motion in the magnetosphere at distances greater than about 4 $R_e$ in the equatorial plane, must be given approximately by superposition of the motions due to rotation of the earth and the circulation corresponding to the Ds current (which we have suggested is due to viscous drag of the solar wind), since the $S_q$ and L current systems are weak at high latitudes. This superposition is indicated for the equatorial plane of the magnetosphere in figure (15). Note that the central streamline, which lies more or less in the sun - earth direction if rotation is not included, is deflected first to the afternoon side and then to the morning side as it passes the earth. This is of some significance since field lines which have been dragged round the surface of the magnetosphere, must move through the interior more or less along this streamline. Thus a concentration of particles captured from the solar wind is to be expected here and we therefore suggest that it will be the locus of greatest activity at ionospheric levels. In contrast there are areas, particularly on the afternoon side of the magnetosphere, in which activity must be relatively low, because the streamlines never approach the surface of the magnetosphere where the field lines could conceivably capture solar particles.

The corresponding net motion at ionospheric levels in the north polar cap is sketched in figure (16). It is noticeable that the central streamline described above, makes a loop which runs from high latitudes, first to the afternoon side, passing through the magnetic midnight meridian at about auroral zone latitudes, and continuing along the auroral zone till the late morning when it moves north once again. One expects greatest activity along this loop, in the sense that that at any given latitude the diurnal variation of activity should show a maximum wherever the loop is intersected. The activity should not be uniform along the loop, since different degrees of acceleration of particles (due to compression) are involved according to the latitude concerned, and also the further particles progress along the loop, the more noticeable the effects of irreversible acceleration become. Thus one expects a general increase of the energy of precipitated particles along the loop, with energies of 1-10 kev occurring on the first section (resulting in sporadic E rather than absorption), and energies of perhaps 100 kev occurring in the morning hours (resulting in radio - wave absorption at D-region levels). Regions of low activity are also predicted in the interior of the loop, and more especially on the evening side at geomagnetic latitudes of about 70°.

This description of the production of ionospheric disturbances is rather well confirmed by observation. The quiet region on the evening side of the polar cap is quite conspicuous for several phenomena -- we have for example, only to consider the transition from quiet to disturbed aurora at about geomagnetic midnight (figure (14)). Plots of the diurnal maxima of sporadic E ionization[65,66], geomagnetic agitation[67], spread F[68], radio absorption[69], radio aurora[70,71], and visual aurora[72] are shown in figure (17) -- these show up in the first part of the loop of activity quite clearly. A study of auroral absorption by Canadian workers[75,76] is shown in figure (18) -- an examination of the contours will reveal the first part of the loop as being relatively weak as far as absorption is concerned, and that the absorption becomes extremely pronounced in the mid-morning hours, as one would expect since irreversible processes are required to produce the necessary energetic electrons in sufficient numbers. The quiet region on the evening side of the polar cap is very clearly indicated in this plot.

If irreverisble acceleration of electrons does in just take place as we have described, then it can be considered a further prediction of the theory that any associated VLF emissions should have a diurnal maximum of occurrence at more or less the same time as does the auroral absorption. In looking for such a maximum however, the screening effects of the absorption must be avoided, thus the emissions should be observed at somewhat lower latitudes than the auroral zone. One would expect that direct observations of electron precipitation (as carried out by Injun I (74)) should also show a maximum in this region, and that the main input of trapped electrons occurs at an equatorial distance of 4-6 $R_e$ on the morning side of the earth.

## REFERENCES


1. Biermann, L., 1951, Z. Astrophys., 29, 274; 1952, Z. Naturforsh, 7a, 127; 1957, Observatory, 107, 109; 1961, "Space Astrophysics" (Ed. W. Liller), McGraw-Hill, 150.

2. Parker, E. N., 1958, Ap.J., 128, 664; 1960a, Ap.J., 132, 175; 1960b, Ap.J., 132, 821; 1961, Ap.J., 133, 1014.

3. Chapman, S., 1957, Smithsonion Contributions to Astrophysics, 2, 1; 1959, Proc. Roy. Soc., A 253, 462.

4. Neugebauer, M. and Snyder, C. W., 1962, Science, 138, 1095.

5. Coleman, P.J., Davis, L., Smith, E. J., and Sonett, C. P., 1962, Science, 138, 1099.

6. Ahluwalia, H. S., and Dessler, A. J., 1963, Planetary and Space Science, 9, 195.

7. Kulikovskii, A. G., 1957, Doklady Akad. Nauk. SSSR, 117, 199.

8. Cole, J. D., and Huth, J. H., 1959, Phys. Fluids, 2, 624.

9. Axford, W. I., 1962, J. Geophys. Res., 67, 3791.

10. Gold, T., 1955, Gas Dynamics of Cosmic Clouds (Ed. M. C. VanderHulst and J. M. Burgers), North-Holland Publ. Coy., Amsterdam.

11. Fishman, F. J., Kantrowitz, A. R. and Petschek, H. E., 1960, Rev. Mod. Phys., 32, 959.

12. Johnson, F. S., 1960, J. Geophys. Res., 65, 3049.

13. Piddington, J. H., 1960, J. Geophys. Res., 65, 93.

14. Chapman, S., and Ferraro, V. C. A., 1931, Terrest. Mag. and Atmospheric Elect., 36, 171.

15. Hones, E. W., 1963 J. Geophys. Res., 68, 1209.

16. Hayes, W. D., and Probstein, R. F., 1959, Hypersonic flow Theory, Academic Press, New York.

17. Harrison, E. R., 1962, Geophys. J. Roy. Astro. Soc., 6, 679.

18. Beard, D. B., 1960, J. Geophys. Res., 65, 3559.

19. Spreiter, J. R., and Briggs, B. R., 1962, J. Geophys. Res., 67, 37.

20. Davis, L., and Beard, D. B., 1962, J. Geophys. Res., 67, 4505.

21. Dungey, J. W., 1955, Proc. Ionosphere Conf., The Physical Society of London, 229.

22. Parker, E. N., 1957, Phys. Fluids, 1, 171.

23. Axford, W. I., 1962, Canadian J. Phys., 40, 654; 1960, Quart. J. Mech. App. Math., 13, 314.

24. Dessler, A. J., 1961, J. Geophys. Res., 66, 3587.

25. Sonett, C. P., Smith, E. J., and Sims, A. R., 1960, Space Research (Ed. by H. K. Kallmann - Bijl), North-Holland Publ. Co., Amsterdam, 921.

26. Van Allen, J. A., 1959, J. Geophys. Res., 64, 1683.

27. Cahill, L. J. and Amazeen, P. G., 1963 J. Geophys. Res. 68, 1835.

28. Freeman, J. W., Van Allen, J. A., Cahill, L. J., 1963, J. Geophys. Res., 68.

29. Frank, L. A., Van Allen, J. A., and Macagno, E., 1963, J. Geophys. Res., 68, 3543.

30. O'Brien, B. J., 1963, J. Geophys. Res., 68, 989.

31. Heppner, J. P., Ness, N. F., Scearce, C. S., and Skillman, T. L., 1963, J. Geophys. Res., 68, 1.

32. Bonetti, A., Bridge, H. S., Lazarus, A. J., Rossi, B., and Scherb, F., 1963, J. Geophys. Res., 68, 4017.

33. Gringauz, K. I., Kurt, V. G., Moroz, V. I., and Shklovskii, I. S., 1960a, Doklady Adad. Nauk. SSSR, 132, 1062; 1960b, Astron. Zh., 37, 716.

34. Gringauz, K. I., 1963, Planetary and Space Sci., 11, 281.

35. Carpenter, D. L., 1963, J. Geophys. Res., 68, 1675.

36. Dessler, A. J., 1962, J. Geophys. Res., 67, 4892.

37. Gold, T., 1959, J. Geophys. Res., 64, 1219.

38. Axford, W. I., and Hines, C. O., 1961, Canadian J. Phys., 39, 1433.

39. Hines, C. O., 1963, Quart. J. Roy. Met. Soc., 89, 1.

40. Hines, C. O., 1963, Planetary and Space Sci., 10, 239.

41. Dungey, J. W., 1963, J. Geophys. Res., 68, 3540.

42. Sonnerup, B. W. Ö., and Laird, M. J., 1962, Cornell University Report, CRSR 130.

43. Axford, W. I., 1963, J. Geophys. Res. (in press).

44. Chapman, S., and Bartels, J., 1950, Geomagnetism, Vol. II, Clarendon Press, Oxford.

45. Dougherty, J. P., 1963, J. Geophys. Res., 68, 2383.

46. Duncan, R. A., 1960, J. Atmospheric and Terrest. Phys., 18, 89.

47. Bandyopodhyay, P., and Montes, H., 1963, J. Geophys. Res. 68, 2453.

48. Harang, L., and Tröim, J., 1960, Planetary and Space Sci., 5, 33.

49. Axford, W. I., 1963, (in preparation).

50. Cole, K. D., 1960, Aust. J. Phys., 13, 484.

51. Fejer, J. A., 1961, Canadian J. Phys., 39, 1409.

52. Nagata, T., and Kokubun, S., 1962, Nature, 195, 555.

53. Davis, T. N., 1960, J. Geophys. Res., 65, 3497; 1962a, Ibid., 67, 59; 1962b, Ibid., 67, 75.

54. Dessler, A. J., and Parker, E. N., 1959, J. Geophys. Res., 64, 2239.

55. Axford, W. I., and Hines, C. O., 1962, J. Geophys. Res., 67, 2057.

56. Reid, G. C., and Rees, M. H., 1961, Planetary and Space Sci., 5, 99.

57. Fejer, J. A., 1963, J. Geophys. Res., 68, 2167.

58. Kern, J. W., 1961, J. Geophys. Res., 66, 1290.

59. Chamberlain, J. W., Kern, J. W., and Vestine, E.H., 1960, J. Geophys. Res., 65, 2535.

60. Kern, J. W., 1962, J. Geophys. Res., 67, 2649.

61. Gold, T., 1962, Space Sci. Rev., 1 , 100.

62. Sonett, C. P., and Abrams, I. J., 1963, J. Geophys. Res., 68, 1233.

63. Chapman, S., 1956, Vistas in Astromony, 2, 912.

64. Wilson, C. R., and Sugiura, M., 1961, J. Geophys. Res., 4097.

65. Hagg, E. L., Muldrew, D., and Warren, E., J. Atmospheric and Terrest. Phys. 14, 345.

66. Thomas, L., 1960, Some ionospheric results obtained during the IGY (Ed. W. J. Beynon), p.172, Elsevier Pub. Coy., Amsterdam.

67. Hope, E. R., 1961, J. Geophys. Res., 66, 747.

68. L. E. Petrie, (Unpublished).

69. Hartz, T. R., Montbriand, L. E., and Vogan, E. L., 1963, Canadian J. Phys., 41, 581.

70. Forsyth, P., Green, F., and Mah, W., 1960, Canadian J. Phys., 38, 770.

71. Green, F., Unpublished report, Upper Atmospheric Institute, University of Saskatchewan.

72. Malville, J. M., 1959, J. Geophys. Res., 64, 1389.

73. Hartz, T. R., 1963, Radio Astronomical and Satellite Studies of the Atmosphere, (Ed. J. Aarons), North-Holland Pub. Coy., Amsterdam.

74. O'Brien, B. J., 1962, J. Geophys. Res., 67, 1227.

CAPTIONS FOR FIGURES

1. Two dimensional flow of a perfectly conducting fluid past a line magnetic dipole and a current carrying wire. The total pressure(fluid + magnetic) is continuous across the boundary of the cavities. The directions of the fluid flow and the magnetic flow and the magnetic field are of no significance, both being reversible.

2. (a) Equatorial section of the magnetosphere looking from above the north pole. The geomagnetic tail (shaded) completely envelopes the low latitude donut (unshaded). The downstream boundary of the tail is dotted to indicate our uncertainty with regard to its extent.

   (b) North-south section of the magnetosphere.

   (c) Elevation of the surface of the magnetosphere showing the surface field lines running between the neutral points ($N_n$, $N_s$). Flow lines of the eastwards surface current are indicated by the dashed lines.

3. Features of the Chapman-Ferraro model of the magnetosphere corresponding to the features sketched in figure (2). The surface elevation (c) is shown as it would appear looking in the sun-earth direction.

4. Counting rate of GM counters carried abroad Pioneers III and IV (after Van Allen[26]).

5. Magnetometer record from Pioneer I (after Sonett, Smith and Sims[25]).

6. Details of the transition occurring at the surface of the magnetosphere as observed by Explorer XII (after Freeman, Van Allen and Cahill[28]).

7. Summary of observed omnidirectional intensities of electrons (energies greater than 40 kev) obtained from Explorers XII and XIV (after Frank, Van Allen and Macagno[29]).

8. Approximate altitude distribution of the charged particle concentration in a period of nearly maximum solar activity (after Gringauz[34]).

9. Equatorial section of the magnetosphere looking from above the north pole and showing the streamlines of the motion due to rotation of the earth (or alternatively, the equipotentials of the corresponding electric field). The geomagnetic tail is shaded as in figure (2).

10. Sketches of the $S_q$ current system in the latitude range 0-90°N. On revising the arrows one obtains approximately the sense of motion of the feet of lines of force in the ionosphere. This motion is combined with the motion due to the rotation of the earth to give the net motion shown in the latitude range 0-90°S. Note the closed cell which is formed at low latitudes during the day.

11. (a) An idealized sketch of the ionospheric motion corresponding to Ds current system in the north polar cap above geomagnetic latitude $\Lambda \approx 60^{\circ}$. The + and - signs indicate the polarization charges

associated with the electric field.

(b) Motion in the equatorial plane of the magnetosphere corresponding to ionospheric motion in (a).

12. The quiet-day current pattern $S_q^p$ for the south polar cap (after Nagata and Kokubun[52]). The current between adjacent lines is $2 \times 10^4$ amp.

13. The proposed circulatory motion in the equatorial plane of the magnetosphere looking from above the north pole. The points A and B and the polarization charges correspond to those in figure (11a). The hatched area indicates the regions in which field lines near the surface of the magnetosphere are dragged along by the solar wind on the exterior.

14. Motion of auroral irregularities (after Davis[53]). Above geomagnetic latitude $80^\circ$, auroral arcs tend to be aligned in the sun-earth direction, as indicated. The wavy lines in the post midnight region at lower latitudes are intended to represent the effects of break-up. The arrows indicate the sense of motion of irregularities.

15. The net motion in the equatorial plane of the magnetosphere obtained by superposition of the motion due to rotation (figure (9)) and viscous interaction with the solar wind (figure (13)). Field lines in the areas denoted $Q_1$ and $Q_2$ do not at any stage move very close to the surface of the magnetosphere.

The hatching in the area surrounding the central streamline is intended to indicate the degree of energization of particles, maximum energization corresponding to the close hatching in the morning hours.

16. The pattern in the north polar cap corresponding to that shown in the interior of the magnetosphere in figure (16).

17. Location of diurnal maxima of various ionospheric disturbance phenomena, namely geomagnetic agitation (I), aurora (II), sporadic E (III), spread F (o), and radio absorption (x).

18. Contour diagram showing the percentage occurrence in time of auroral absorption of 1 db or more as a function of geomagnetic latitude and mean geomagnetic time (after Hartz, Montbriand and Vogan[75]).

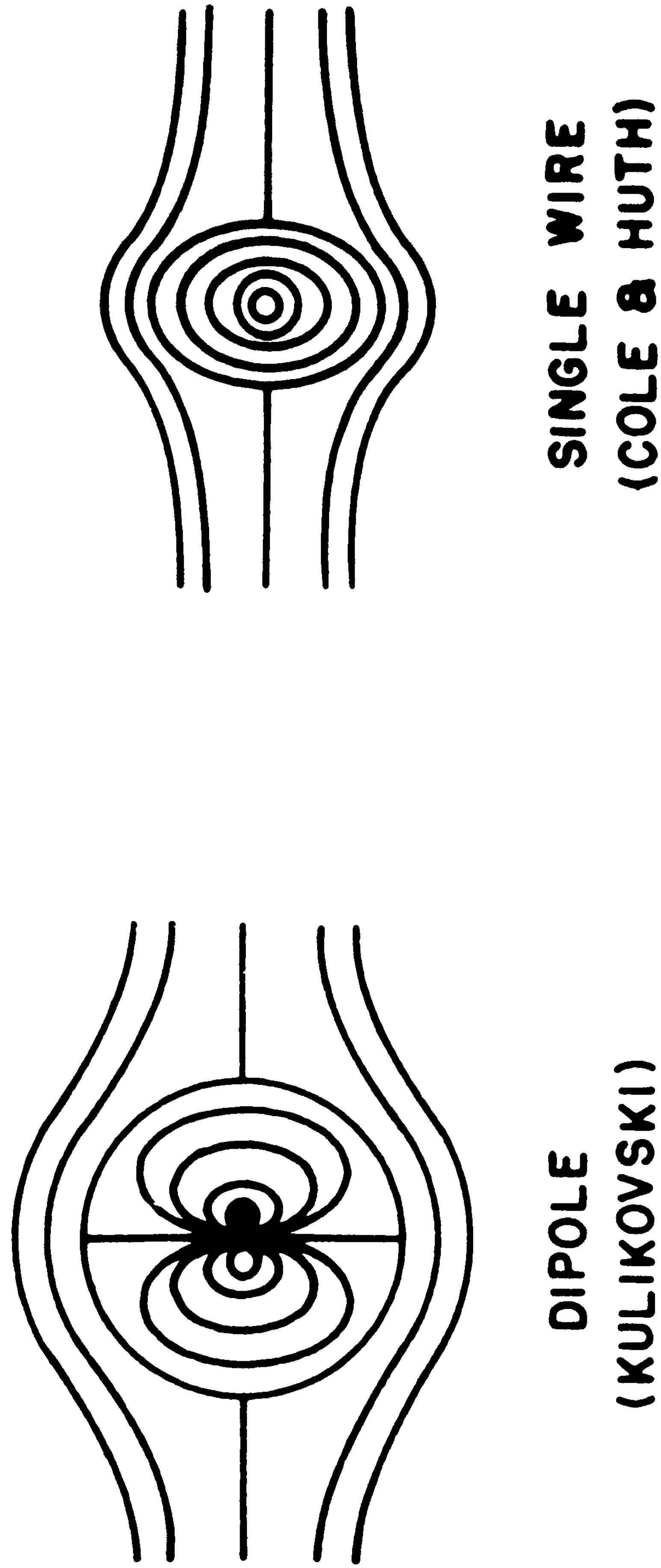
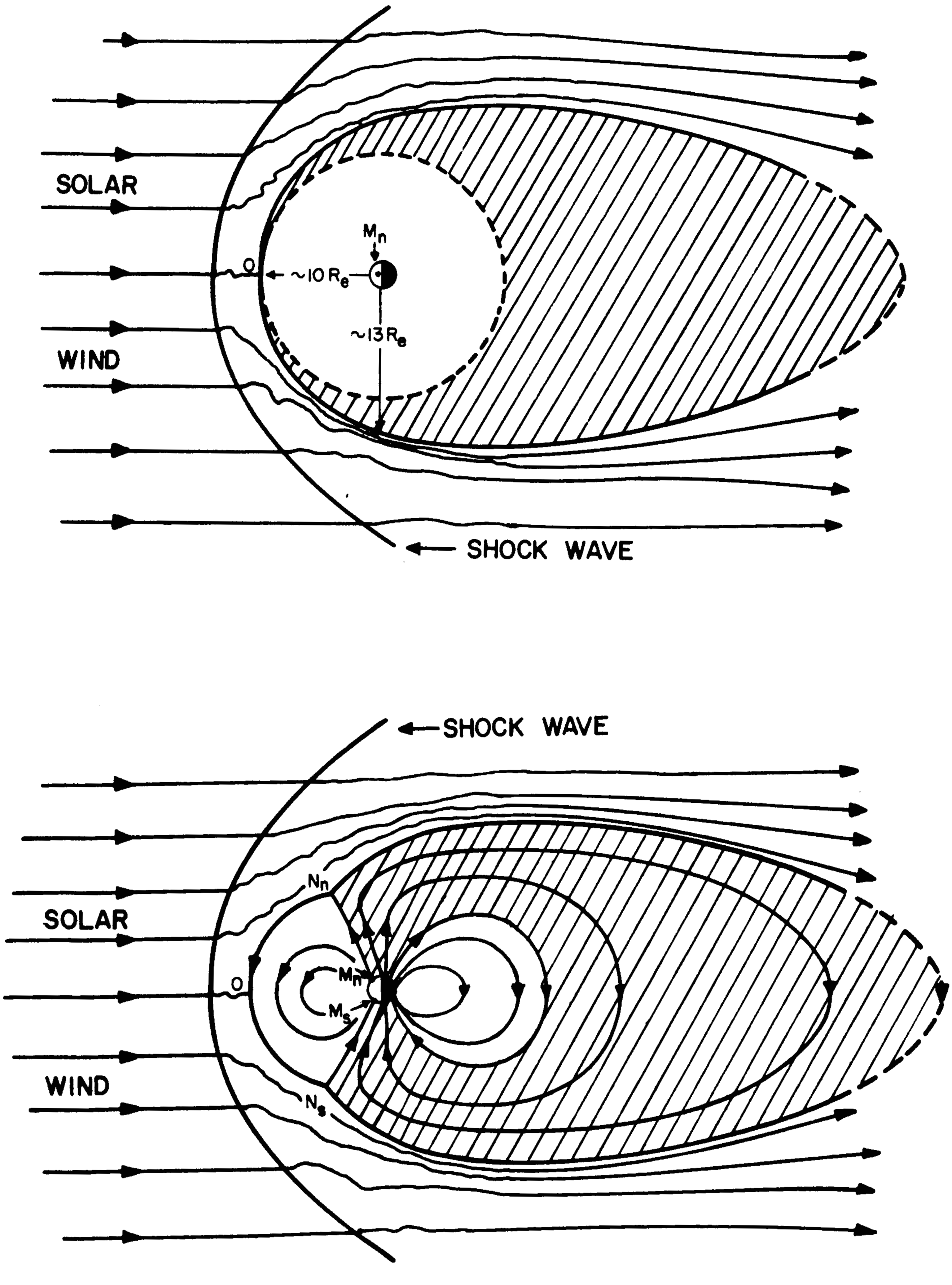



FIGURE 1




FIGURES 2(a) and 2(b)

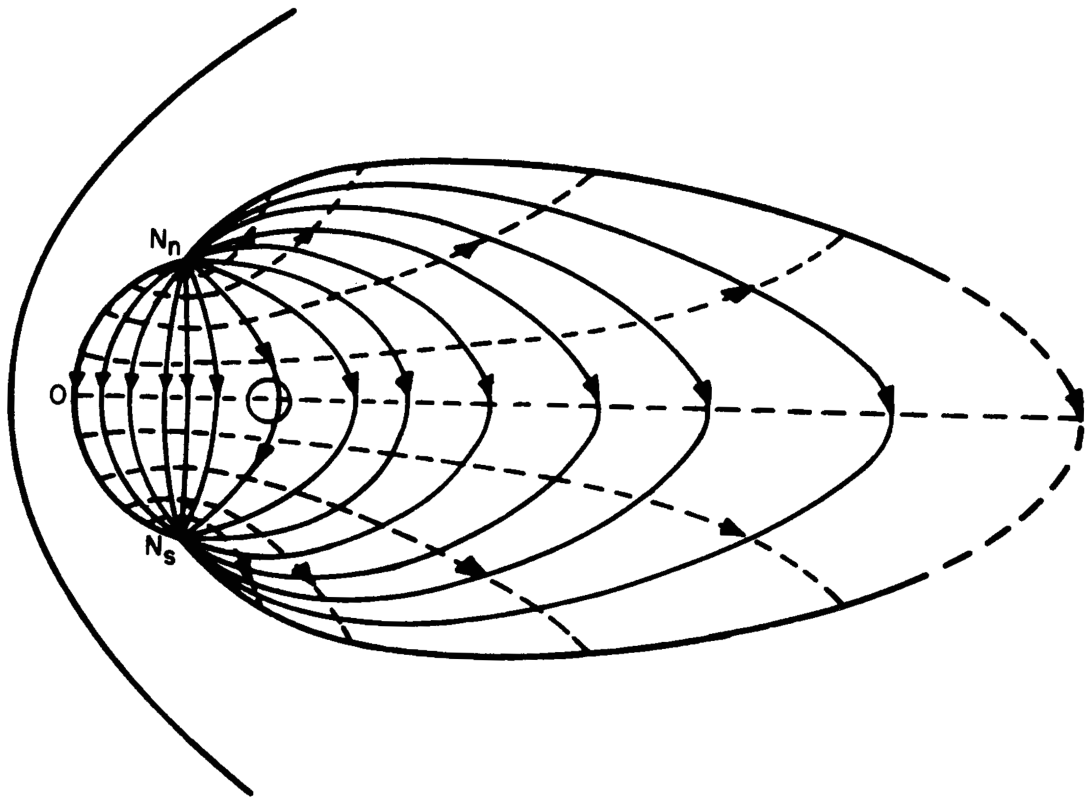
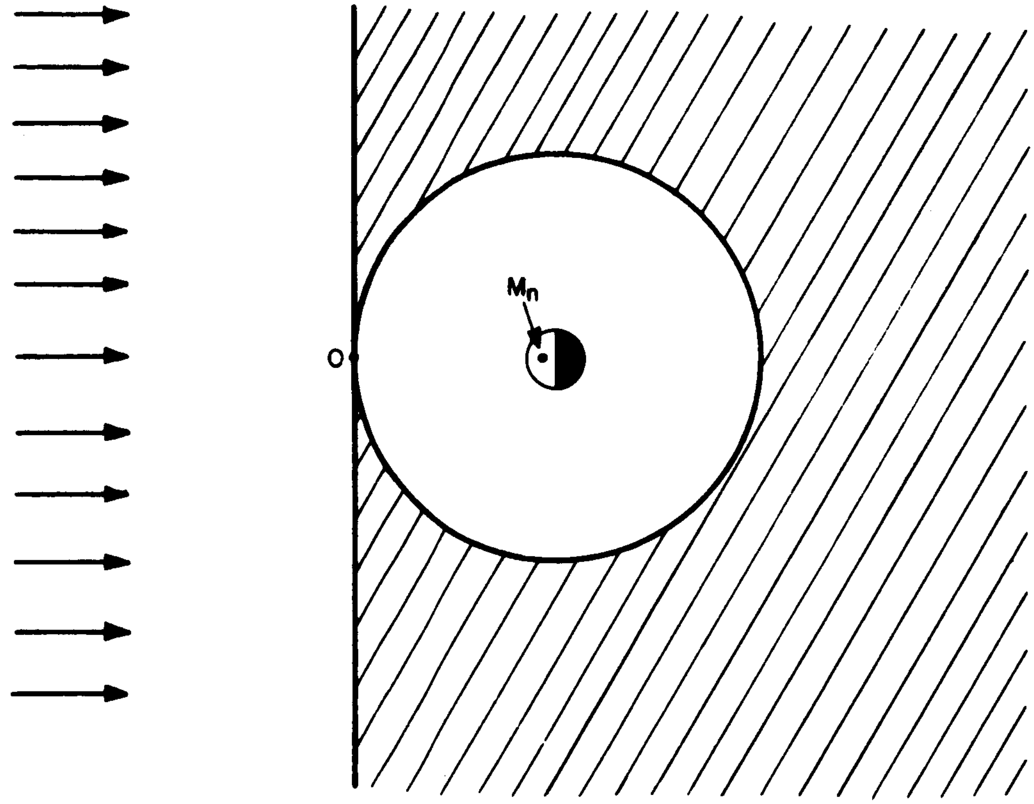
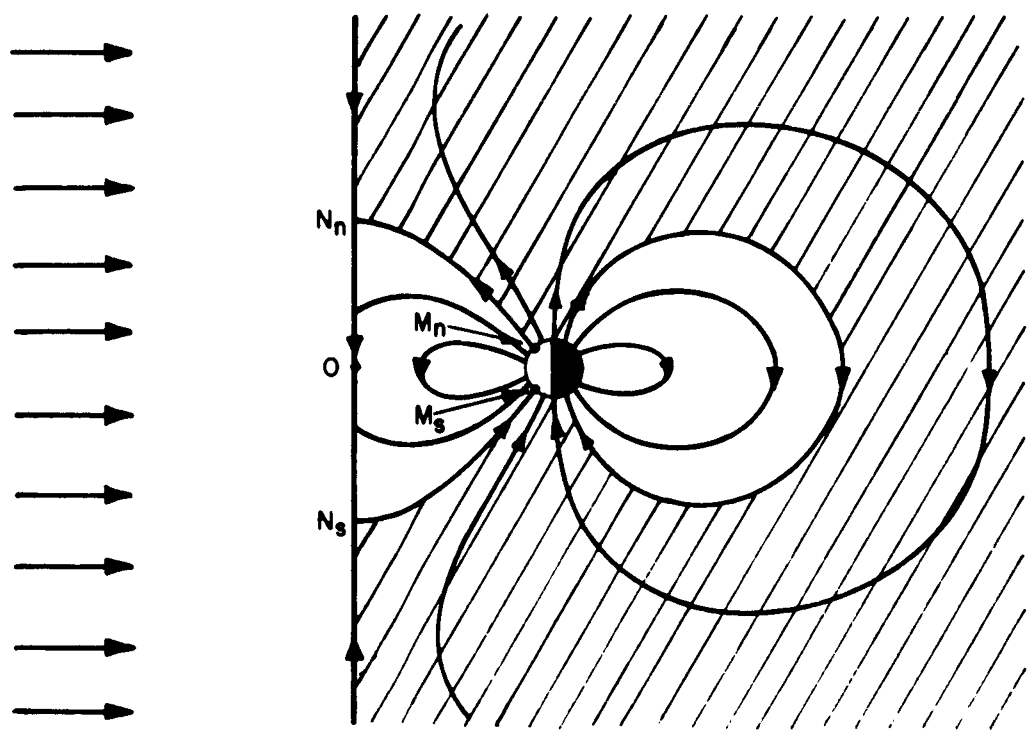



FIGURE 2(c)




FIGURES 3(a) and 3(b)

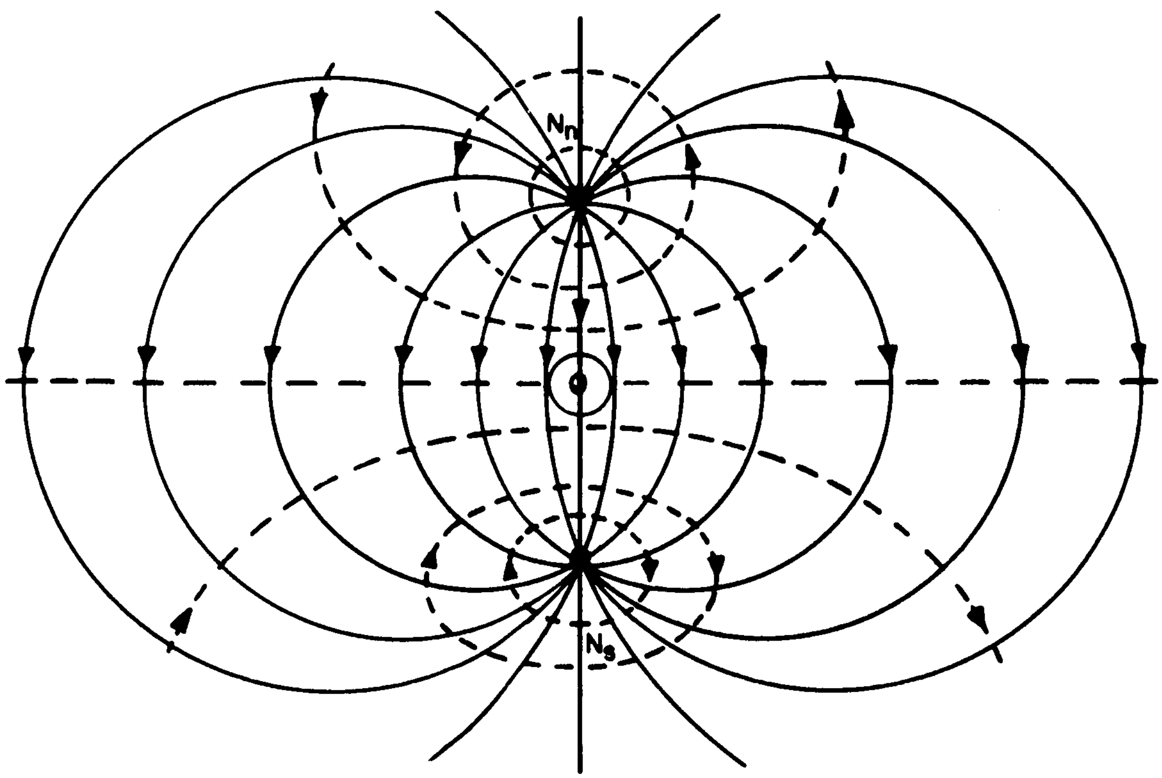
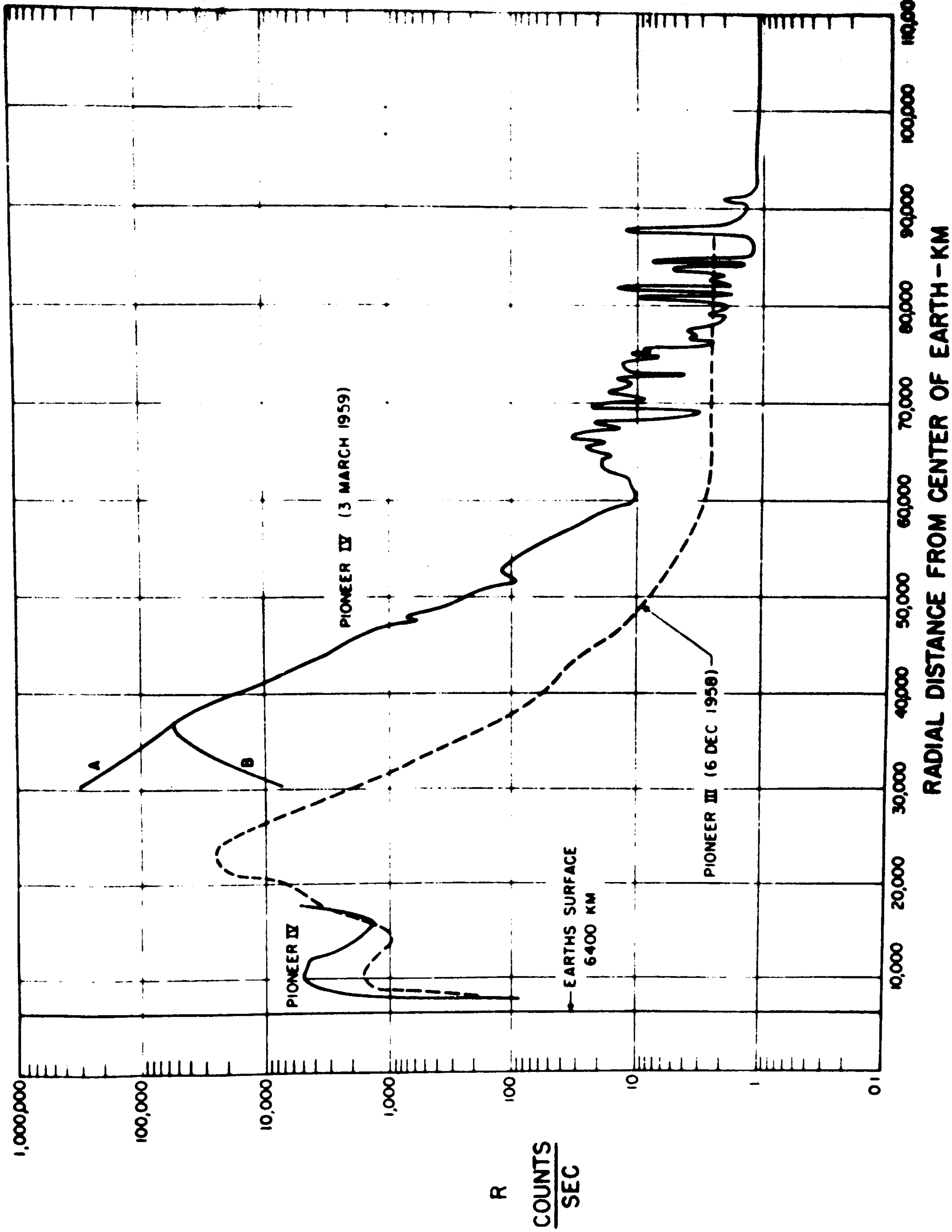



FIGURE 3(c)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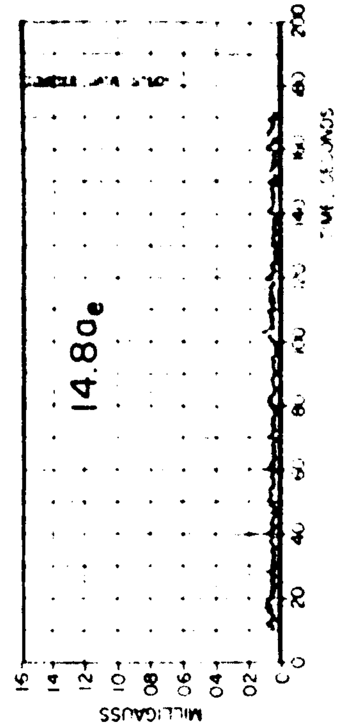
70,000
80,000
90,000
100,000
110,000
PIONEER IV (3 MARCH 1959)
PIONEER IV
PIONEER III (6 DEC 1958)
EARTHS SURFACE
6400 KM
A
B

FIGURE



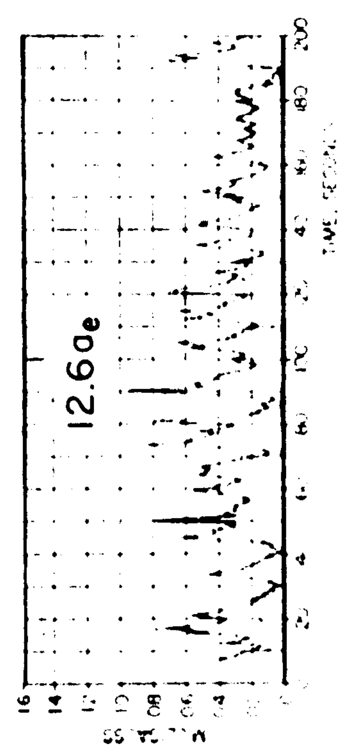
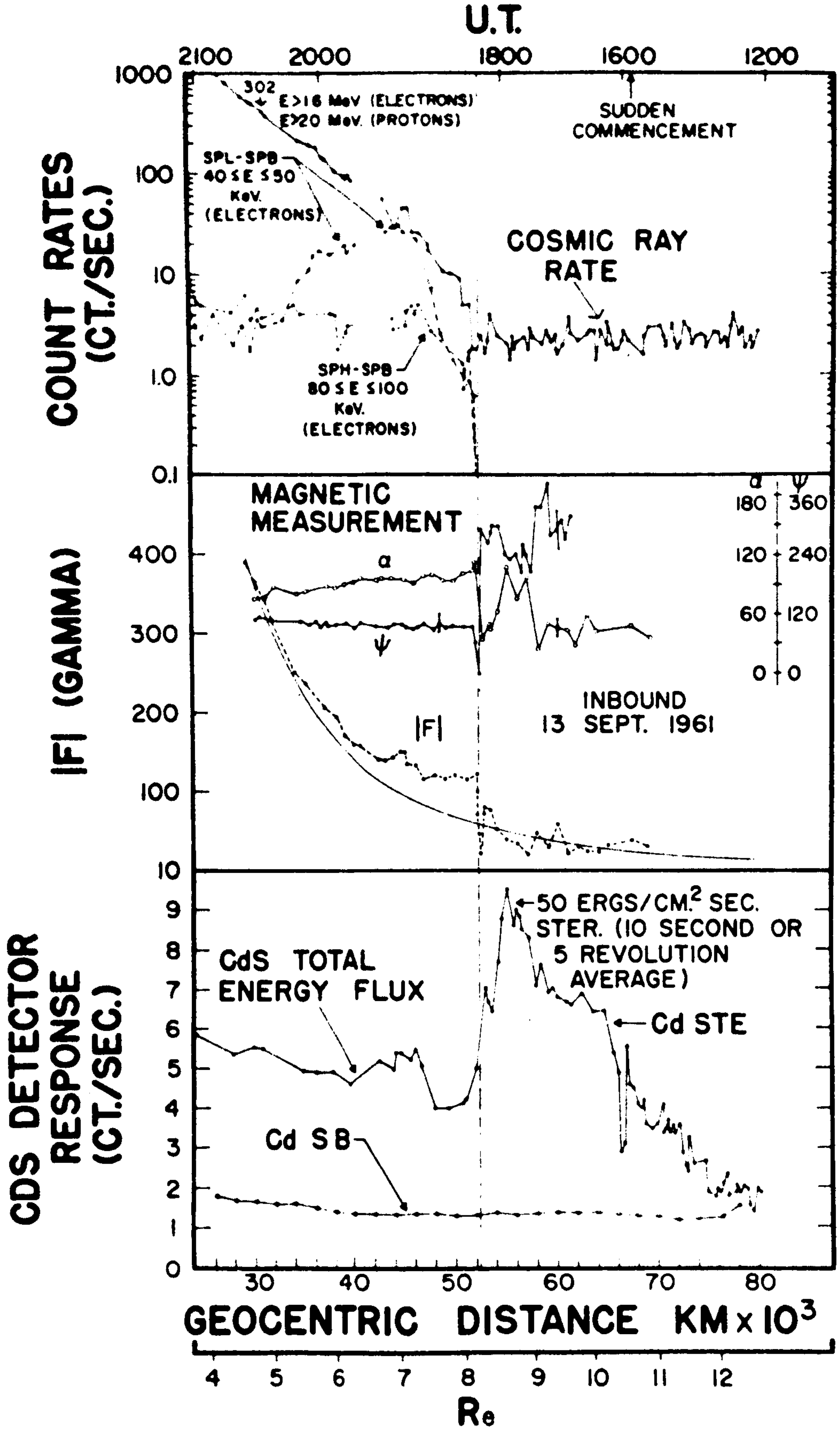




FIGURE 5


U.T.
2100
2000
1800
1600
1200
302
E>16 MeV (ELECTRONS)
E>20 MeV (PROTONS)
SUDDEN COMMENCEMENT
SPL-SPB
40 ≤ E ≤ 50 KeV. (ELECTRONS)
COSMIC RAY RATE
SPH-SPB
80 ≤ E ≤ 100 KeV. (ELECTRONS)
COUNT RATES (CT./SEC.)
1000
100
10
1.0
0.1
MAGNETIC MEASUREMENT
α
ψ
|F|
INBOUND 13 SEPT. 1961
|F| (GAMMA)
400
300
200
100
10
180 360
120 240
60 120
0 0
CdS TOTAL ENERGY FLUX
50 ERGS/CM.² SEC. STER. (10 SECOND OR 5 REVOLUTION AVERAGE)
Cd STE
Cd SB
CDS DETECTOR RESPONSE (CT./SEC.)
0 1 2 3 4 5 6 7 8 9 10
30 40 50 60 70 80
GEOCENTRIC DISTANCE KM x 10³
4 5 6 7 8 9 10 11 12
Re

FIGURE

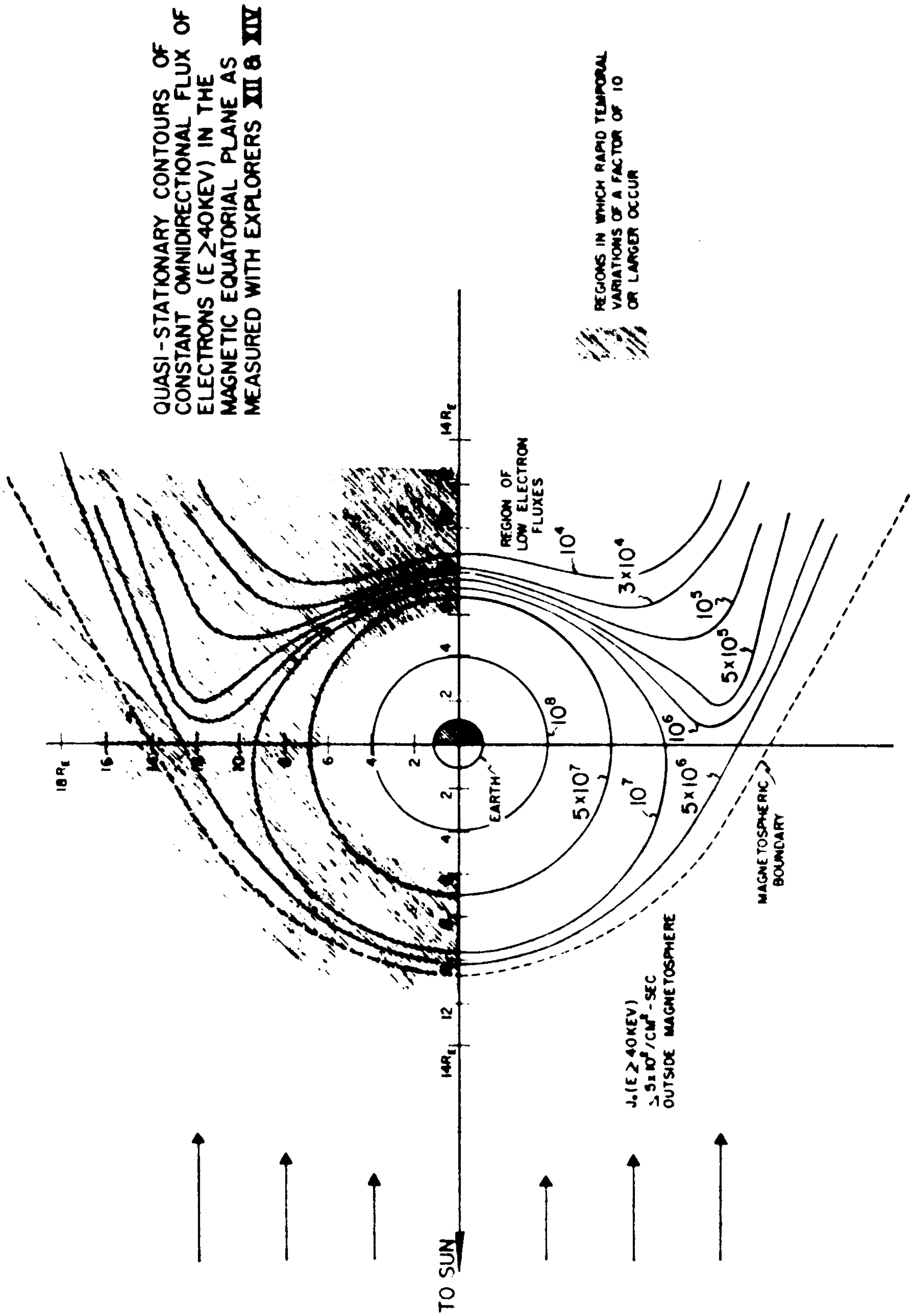

QUASI-STATIONARY CONTOURS OF CONSTANT OMNIDIRECTIONAL FLUX OF ELECTRONS (E ≥ 40KEV) IN THE MAGNETIC EQUATORIAL PLANE AS MEASURED WITH EXPLORERS XII & XIV
REGIONS IN WHICH RAPID TEMPORAL VARIATIONS OF A FACTOR OF 10 OR LARGER OCCUR
REGION OF LOW ELECTRON FLUXES
$10^4$
$3\times10^4$
$10^5$
$5\times10^5$
$10^6$
$10^8$
$5\times10^7$
$10^7$
$5\times10^6$
EARTH
MAGNETOSPHERIC BOUNDARY
$J_0(E \geq 40KEV)$ $\leq 5\times10^2/CM^2$-SEC OUTSIDE MAGNETOSPHERE
TO SUN
$18R_E$
16
14
12
10
8
6
4
2
$14R_E$
$14R_E$
12

FIGURE 7

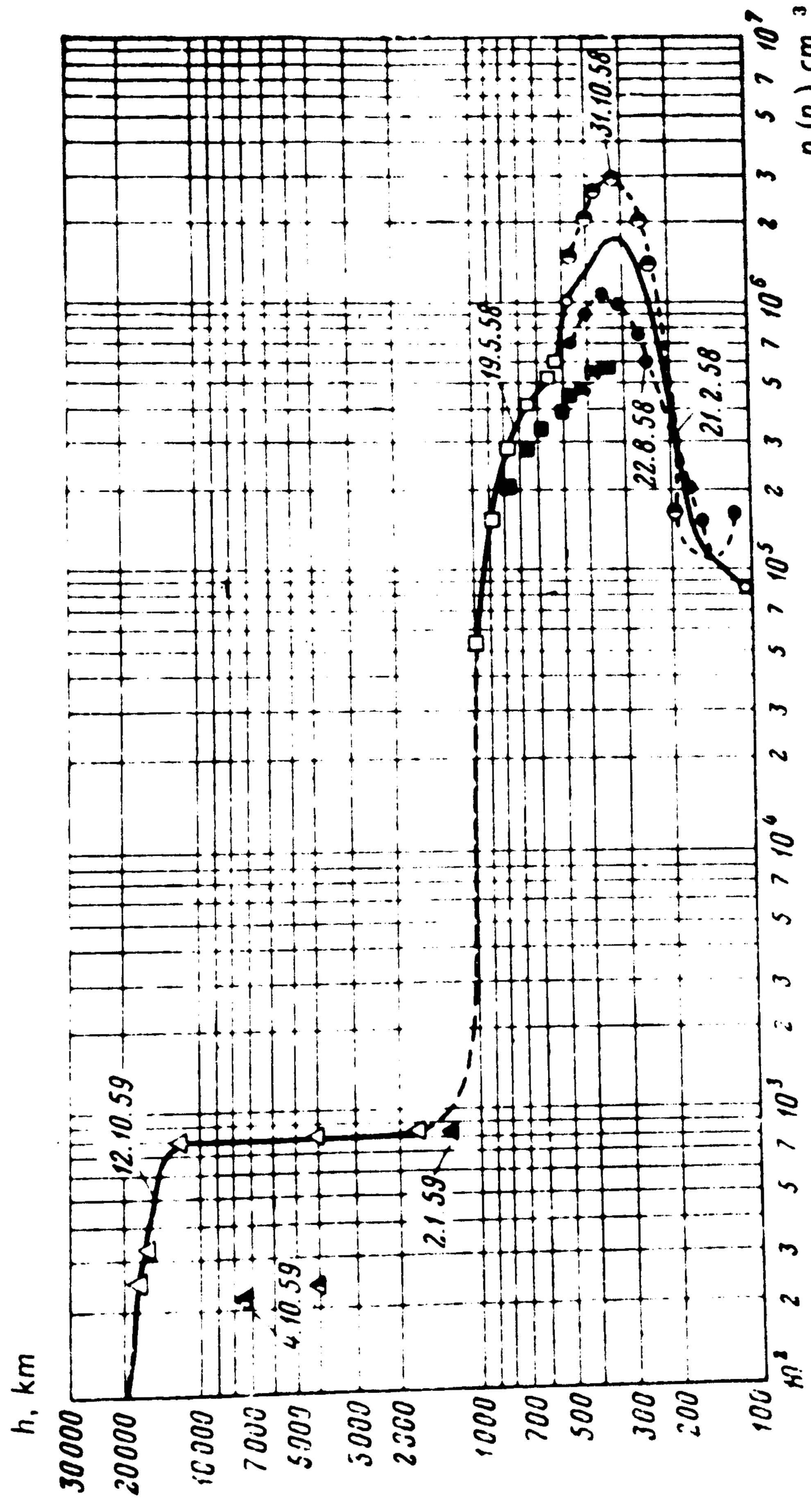

h, km
30000
20000
10000
7000
5000
3000
2000
1000
700
500
300
200
100
12.10.59
4.10.59
2.1.59
19.5.58
31.10.58
22.8.58
21.2.58


FIGURE 8

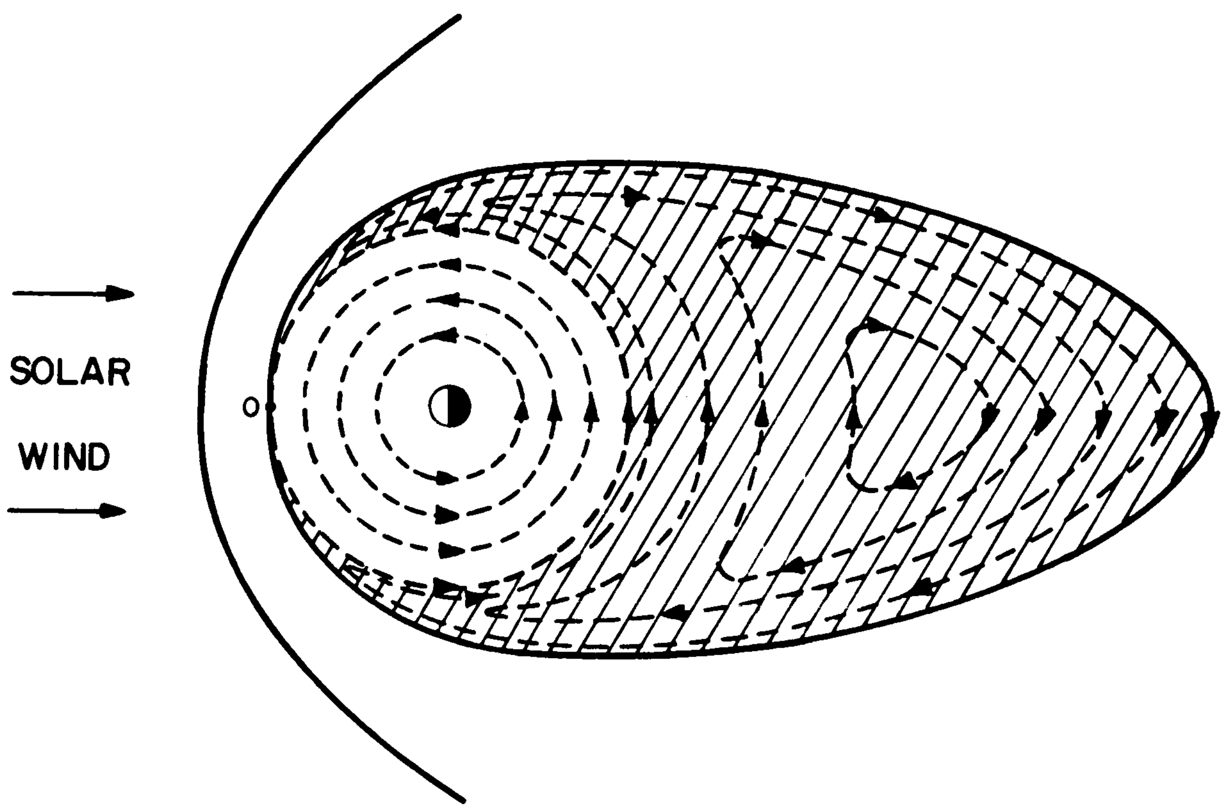



FIGURE 9

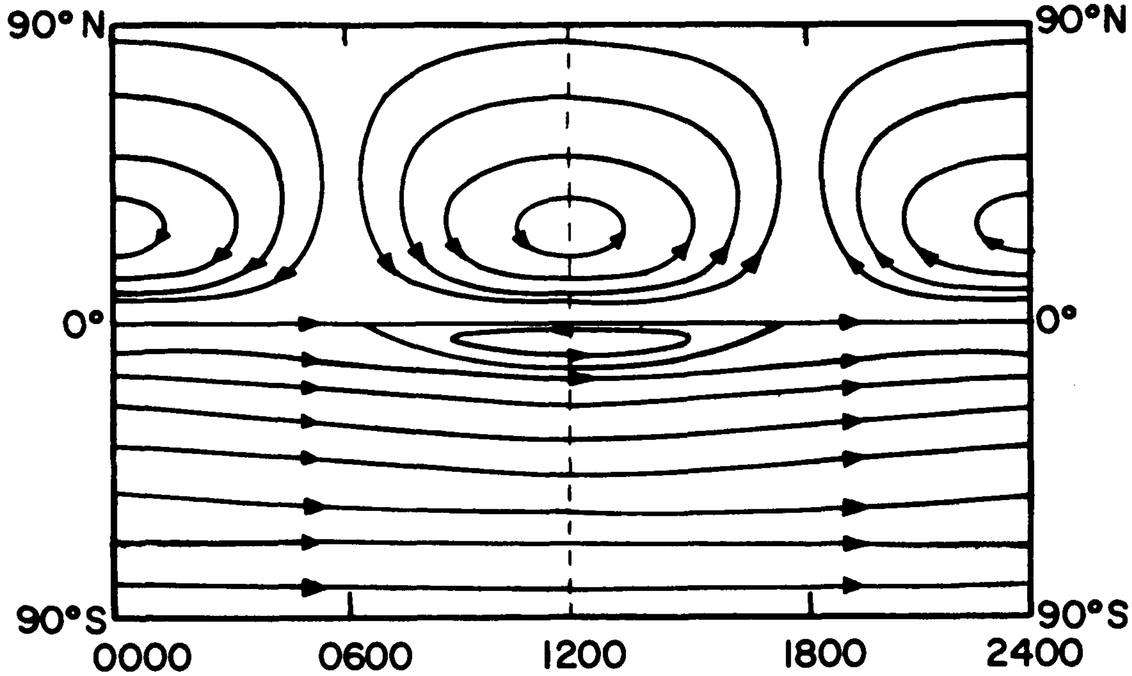
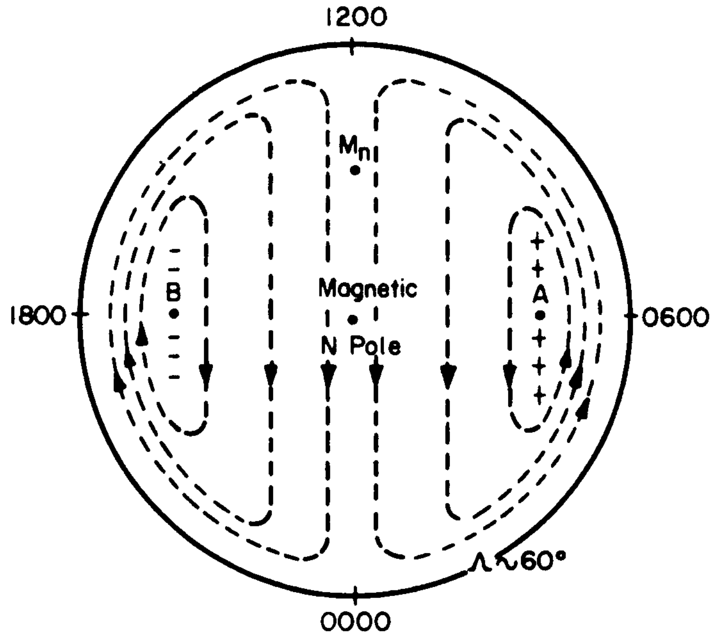
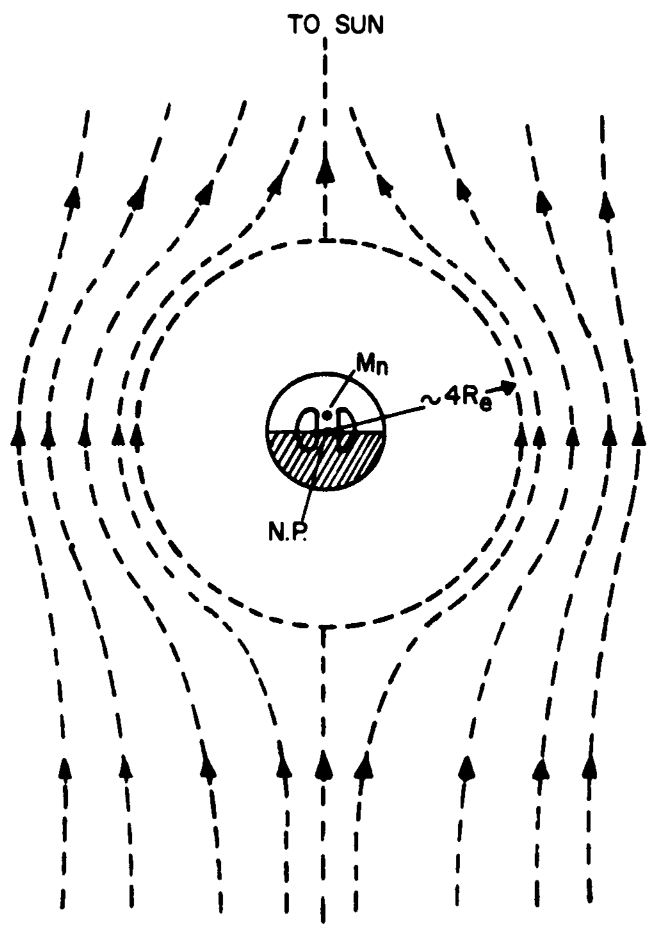



FIGURE 10




FIGURES 11(a) and 11 (b)

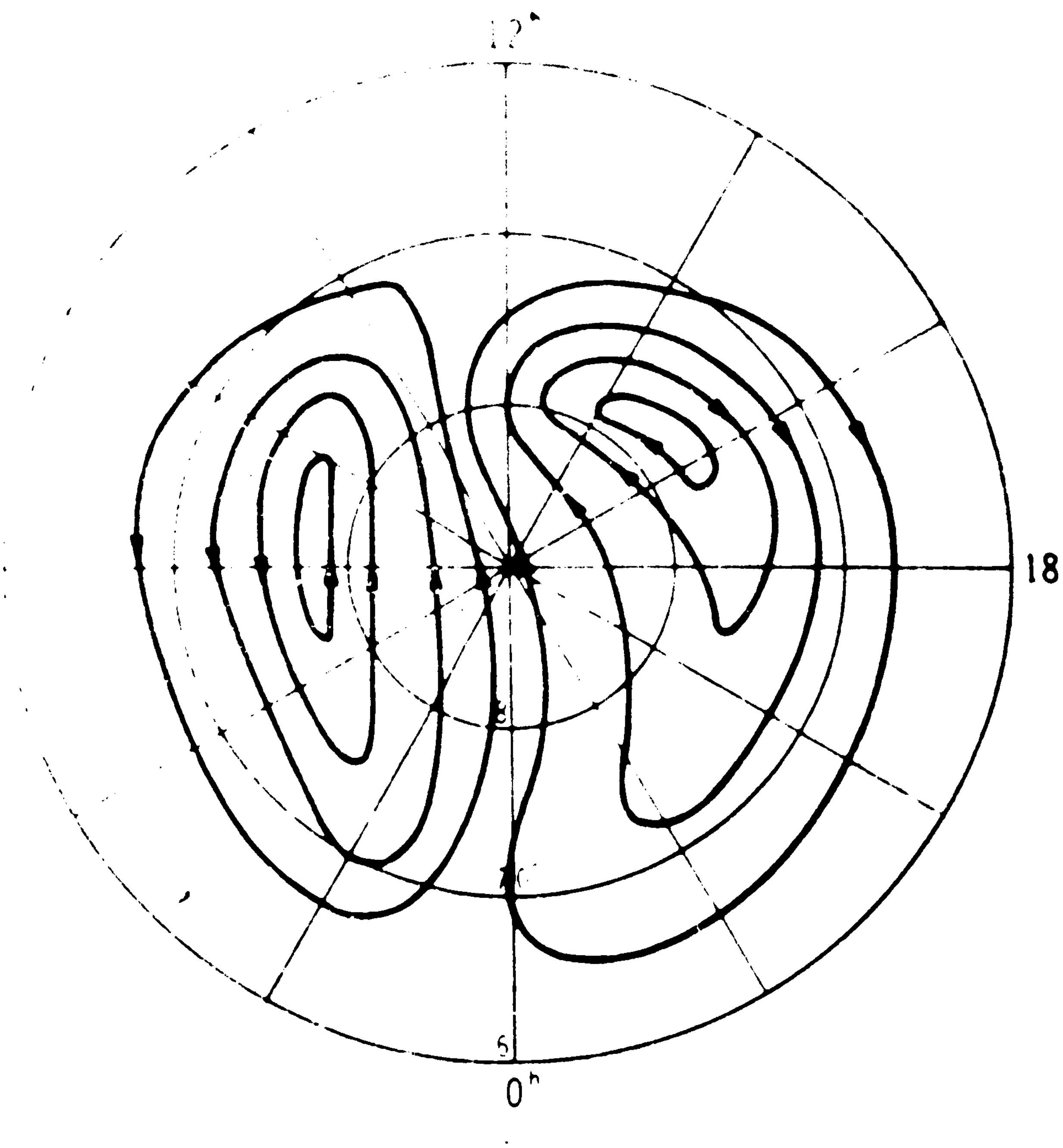



FIGURE 12

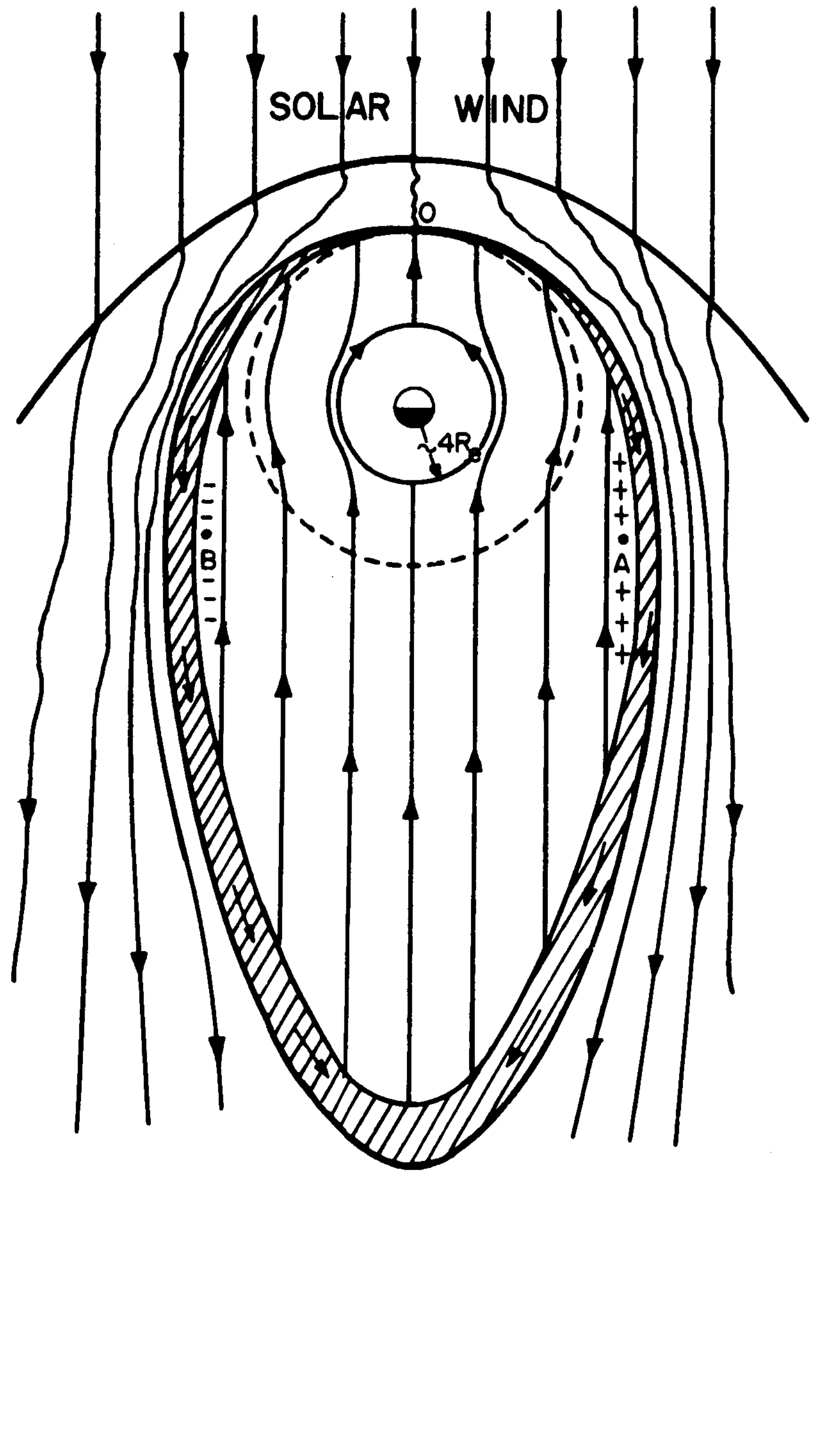



FIGURE 15

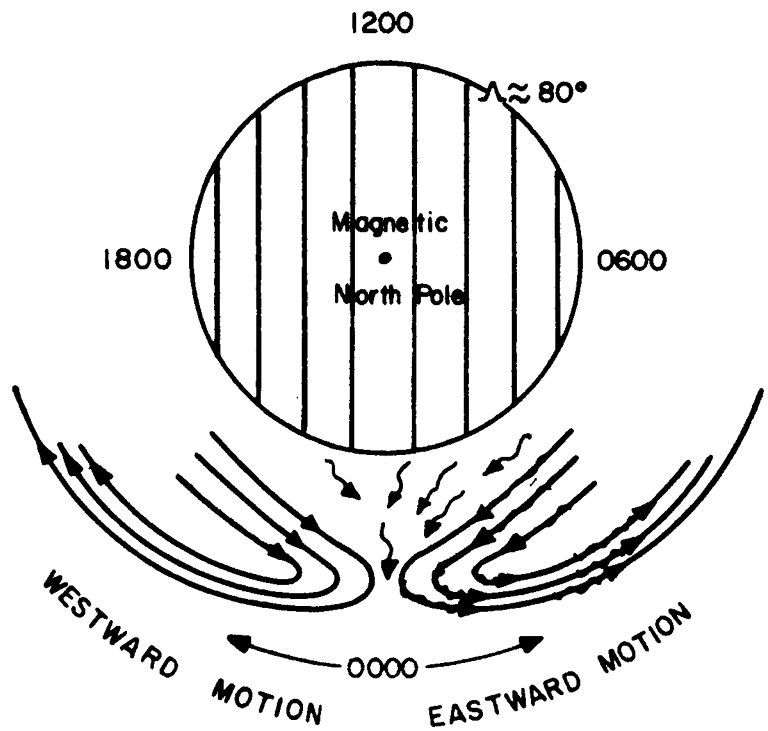

1200
$\Lambda \approx 80°$
1800
0600
Magnetic
North Pole
WESTWARD MOTION
0000
EASTWARD MOTION

FIGURE 14

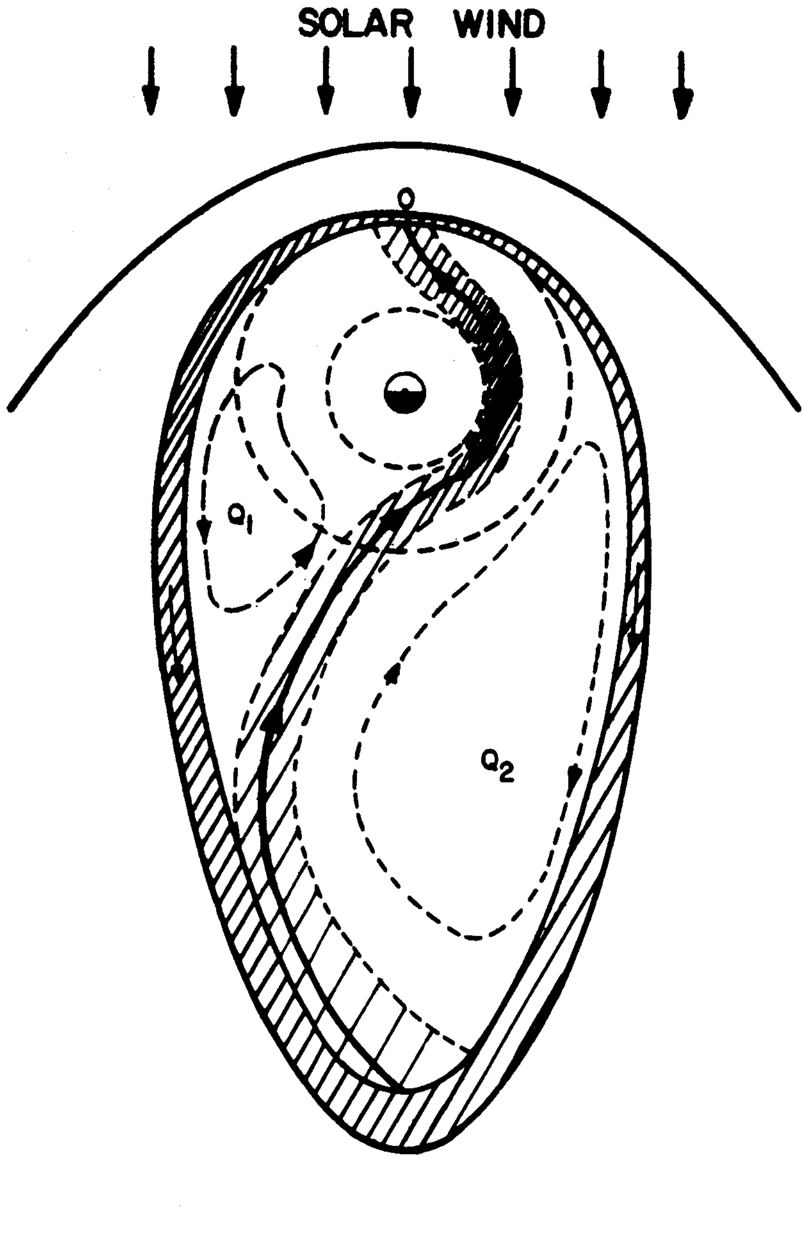
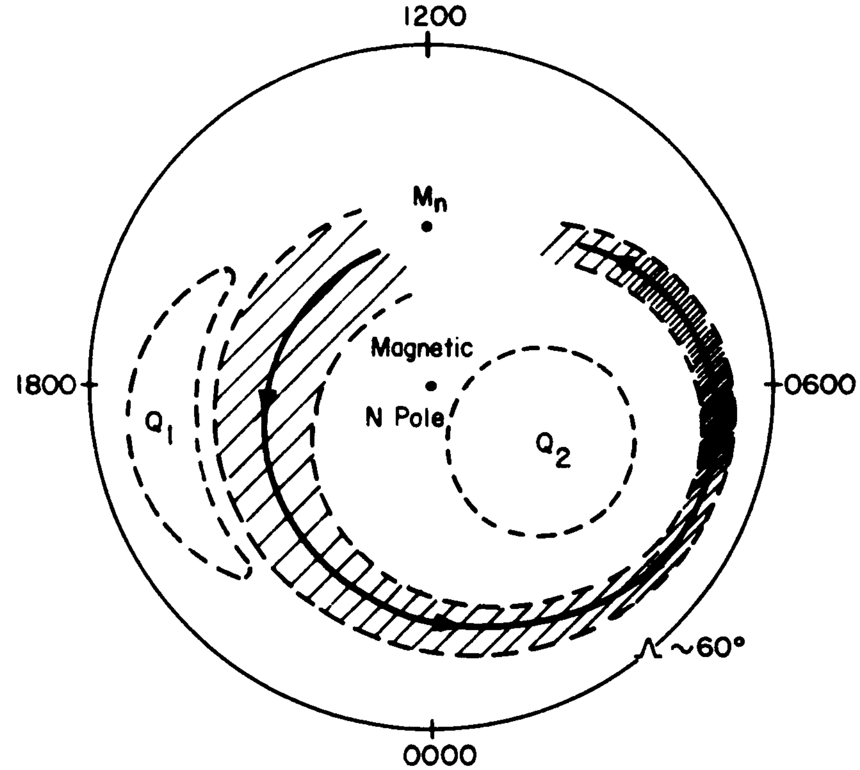
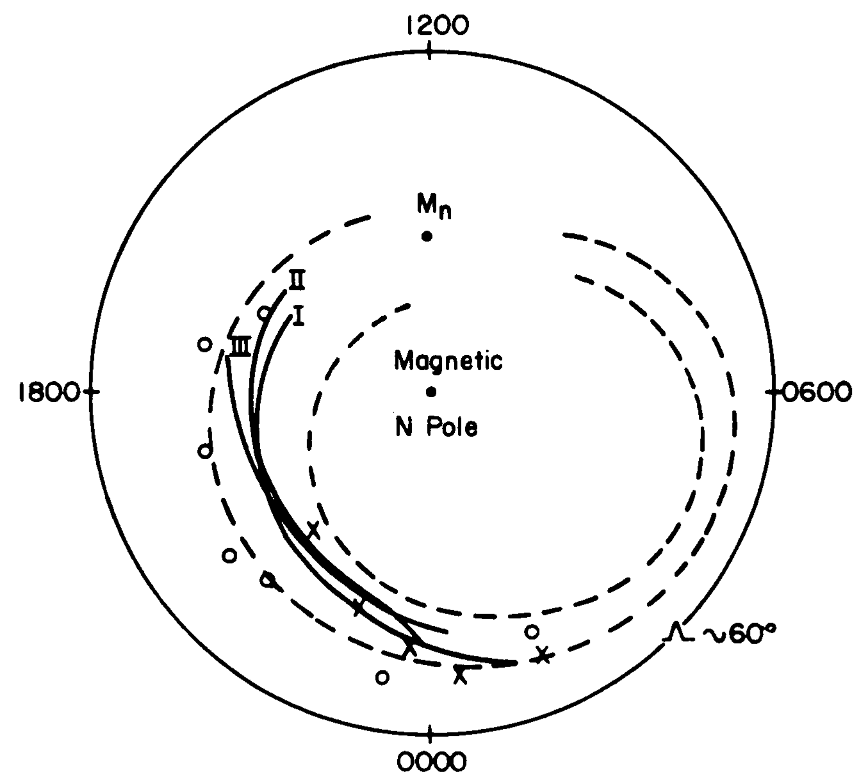
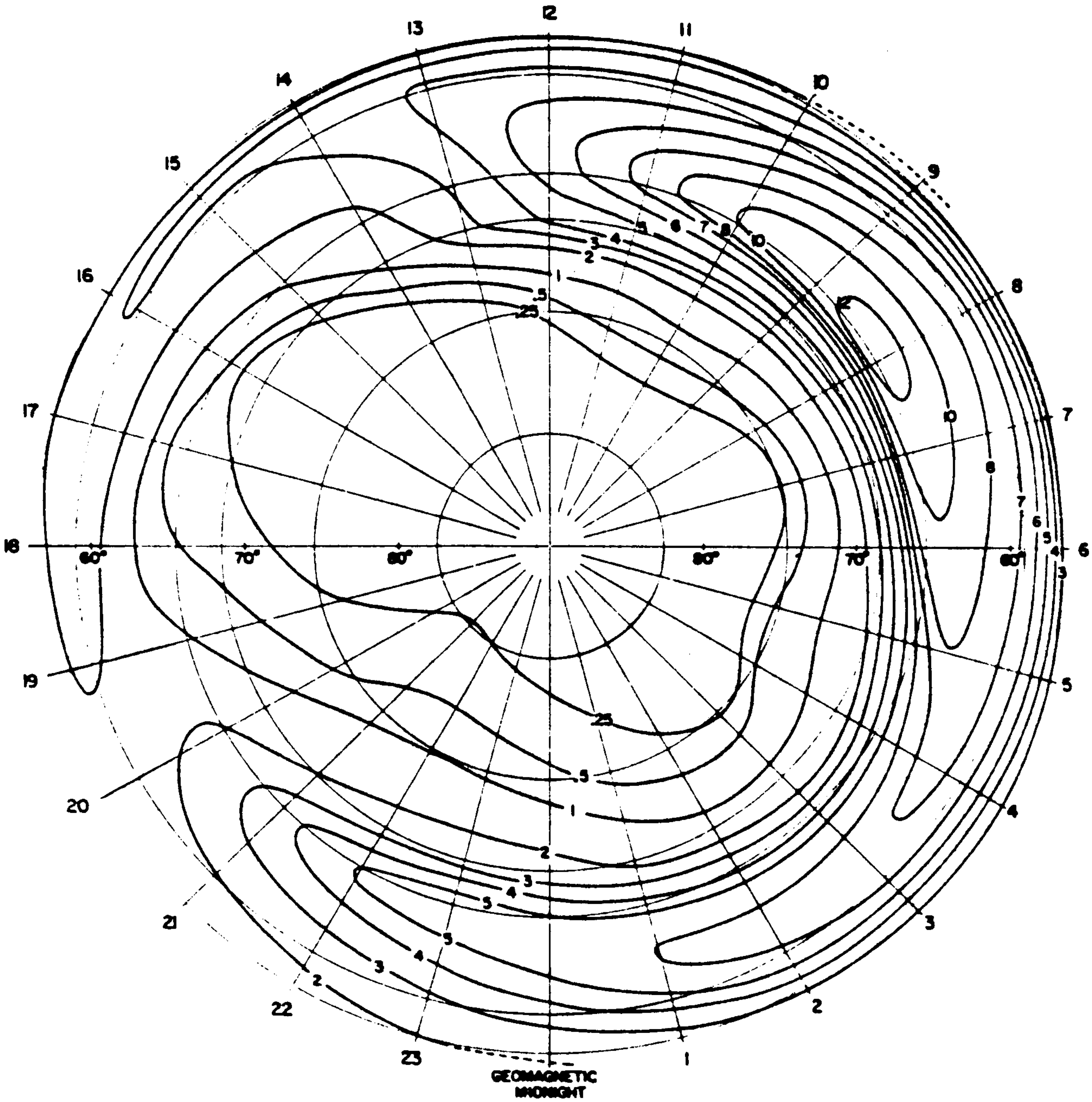



FIGURE 15




FIGURES 16 AND 17



12
13
11
14
10
15
9
16
8
17
7
18
60°
70°
80°
80°
70°
60°
6
19
5
20
4
21
3
22
2
23
1
GEOMAGNETIC
MIDNIGHT


FIGURE 18